US Army Corps of Engineers
Hydrologic Engineering Center

Certification Report

HEC-FDA, Flood Damage Reduction Analysis Software

Version 1.2.4
November 2008

Model Name:	HEC-FDA
Functional Area:	Flood Risk Management
Model Proponent:	Harry Kitch, HQ
Model Developer/Contact:	CEIWR-HEC
Year Developed:	Current version 1.2.4

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Abbreviations

EC	Engineer Circular
EGM	Economic Guidance Memorandum
EM	Engineer Manual
ER	Engineer Regulation
ERDC	Engineer Research and Development Center (USACE)
ETL	Engineer Technical Letter
FCSDR	Flood & Coastal Storm Damage Reduction
FEMA	Federal Emergency Management Agency
FOA	Field Operating Activity
GIS	Geographic Information System
HEC	Hydrologic Engineering Center
HEC-FDA	Flood Damage Reduction Analysis
IWR	Institute for Water Resources
LP3	Log Pearson Type III
NCR	National Research Council
PCX	Planning Center of Expertise
PF	Probability of Failure
PMIP	Planning Models Improvement Program
PRA	Portfolio Risk Assessment
PROSPECT	Proponent-Sponsored Engineer Corps Training Program
USACE	United States Army Corps of Engineers

SECTION 1

Introduction

1.1 Model Purpose

HEC-FDA (subsequently referred to as "the model") is a planning model for flood risk management studies and was developed through collaborative research between Institute for Water Resources (IWR) and Hydrologic Engineering Center (HEC). HEC-FDA has been designed to be an analytical tool used for formulation and evaluating flood risk management plans using risk analysis methods.

In accordance with the Planning Models Improvement Program (PMIP): Model Certification (USACE Engineer Circular No. 1105-2-407, May 2005), certification is required for all planning models developed and/or used by the US Army Corps of Engineers (USACE). The objective of model certification is to ensure that models used by USACE are technically and theoretically sound, computationally accurate, and in compliance with USACE planning policy.

1.2 Model Certification

The model has been reviewed in accordance with requirements for the certification of planning models as identified in EC 1105-2-407 and "Protocols for Certification of Planning Models", under the Planning Models Improvement Program.

Following the definitions in EC 1105-2-407, HEC-FDA is intended for certification as a Corporate Model, in that it has been developed by a USACE laboratory or field operating activity (FOA) and has nationwide implementation. HEC-FDA was developed at HEC, an FOA, and as shown by the results of the PMIP survey, has nationwide implementation.

Levels of effort required in the certification of planning models vary according to the nature of the model to be reviewed. HEC-FDA is a highly complex model compiled in a specialized programming language and contains multiple routines and computational functions. There is considered to be a high risk associated with investment decision-making based on the output of the model, since in most applications it will be used to evaluate flood risk management projects, used as an alternative analysis tool, and secondarily to be used for levee certification. Following these characterizations, a Level 4 review, as defined by the PMIP protocols, is appropriate for HEC-FDA. In accordance with these protocols, the review team may consist of internal experts as deemed appropriate by the Flood Damage Reduction Planning Center of Expertise (PCX).

This report presents the methodology and results of the review and certification process and will make recommendations affecting the level of certification appropriate for the current version of the model (Version 1.2.4). HEC-FDA is intended for certification as a USACE Corporate Model.

1.3 Contribution to Planning Effort

USACE requires the use of risk analysis procedures for formulating and evaluating flood risk management measures. Such projects are generally only authorized and implemented when they are economically justified, that is, when the predicted benefits can be demonstrated to exceed the estimated costs. The required analysis involves the estimation of benefits and costs under different alternatives over a project analysis period, while taking into account the probabilistic nature of storm damage, and the uncertainty regarding the measurement of many input variables. Benefits are derived by comparing the expected damages when a flood damage protection project is in place (the "with project" condition) with the expected damages in the absence of any project (the "without project" condition). HEC-FDA is intended to provide users in the planning community with a standard analytical tool to calculate flood damages and benefits under these conditions.

1.4 Report Organization

The report is organized as follows: an overview of HEC-FDA and description of the model, its inputs, key functions, components and elements are provided in Section 2; Section 3 presents the model evaluation, including the certification criteria, model testing approach and model assessment; and Section 4 presents conclusions and recommendations.

SECTION 2

Model Description

2.1 Model Overview

2.1.1 Model Approach

HEC-FDA allows the user to perform plan formulation and project performance for flood risk management studies. Both economic flood damage and hydrologic engineering analyses are performed using a consistent study configuration (streams, damage reaches, plans, and analysis years). Three types of evaluations are available: expected annual damage (EAD), equivalent annual damage, and project performance by analysis years. Computations and display of results are consistent with technical procedures described in EM 1110-2-1619 and ER 1105-2-101.

The HEC-FDA software provides the capability to perform an integrated hydrologic engineering and economic analysis during the formulation and evaluation of flood risk management plans. The software follows functional elements of a study involving coordinated study layout and configuration, hydrologic engineering analyses, economic analyses, and plan formulation and evaluation. The model will be used continuously throughout the planning process as the study evolves from the base year without-project condition analysis through the analyses of alternative plans over their project life. Hydrologic engineering and economics (flood inundation damage analyses) are performed separately, in a coordinated manner after specifying the study configuration and layout, and merged for the formulation and evaluation of the potential flood risk management plans.

USACE requires the use of risk analysis procedures for formulating and evaluating flood risk management measures (EM 1110-2-1619, ER 1105-2-101). These documents describe how to quantify uncertainty in discharge-exceedance probability, stage-discharge, stage-damage functions, geotechnical probability of failure relationship, and incorporate it into economic and engineering performance analyses of alternatives. The process applies Monte Carlo simulation, a numerical-analysis procedure that computes the expected value of damage while explicitly accounting for the uncertainty in the basic parameters used to determine flood inundation damage. HEC has developed the HEC-FDA software to assist in analyzing flood risk management plans using these procedures. Expected and/or equivalent annual damage are computed in the evaluation portion of the program.

2.1.2 Model Inputs

HEC-FDA requires a significant amount of data from external sources, and the input data requirements vary according to the size of a study. The following provides a basic outline of the individual datasets required by HEC-FDA. These inputs are described in more detail in Section 2.2.

- Study Configuration Data – the basic data defined for a study area; the physical stream locations (streams, damage reaches) and specific plans (analysis years, plans). This data is common for all analyses, and is required for an assignment in HEC-FDA which is an integral part of the model.
- Water Surface Profiles– a water surface profile set must consist of eight flood events and can be discharge- or stage-based for each stream in the study area. Water surface profile data may be used to develop discharge-probability functions, stage-discharge functions, and stage-damage functions.
- Exceedance Probability Functions – for economic and performance analyses an exceedance probability function is required. An exceedance probability function is the relationship between flood magnitude and the probability of exceeding that magnitude. This data maybe defined in terms of discharge (flow) or stage. This relationship can be defined through statistical or hydrologic analyses.
- Regulation Inflow-Outflow Functions – for reservoir operation and modification to unregulated exceedance probability function (if using flow). In the model this is referred to as the transform flow relationship and is entered with a defined exceedance probability function. This functions is used to define a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the exceedance probability function.
- Stage-Discharge Functions – stage-discharge functions are required when an exceedance probability function is defined in terms of discharge. The stage discharge function is used to transform the discharge into stage (and subsequently damage) for each probability. A stage-discharge function is the relationship between discharge (flow) at a river cross-section and the stage (depth) produced by that discharge. This relationship can be defined through a gage or hydraulic analysis.
- Levee Data – levee data includes the top of levee stage, failure characteristics, interior versus exterior stage relationships associated with the levee, or wave overtopping criteria.
- Damage Categories – damage category data includes a name, description, and price index (updates the monetary values of the structure that will be assigned to a damage category).
- Structure Occupancy Type Data – structure occupancy type data includes depth-percent damage functions (structure, content, and other); content-to-structure value ratio; and, the uncertainties in the first floor elevation, value ratios, and the damage in the depth-damage functions.
- Structure Modules – structure module data includes a name, a description, and an assignment to a plan and analysis year.
- Structure Inventory Data – a structure inventory is a record of the attributes of unique or groups of structures relevant to flood damage analysis. Structure inventory data is used to compute an aggregated stage-damage function by damage category at the damage reach index location station.
- Stage-Damage Functions – stage-damage functions are the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given stream or damage reach. The model can compute stage-damage functions, if depth-percent damage functions, water surface profiles, exceedance probability functions, stage-discharge functions, first floor elevations, structure and content values are provided.

The basic relationships between the most signification sets of HEC-FDA input data are shown in Figure 1.

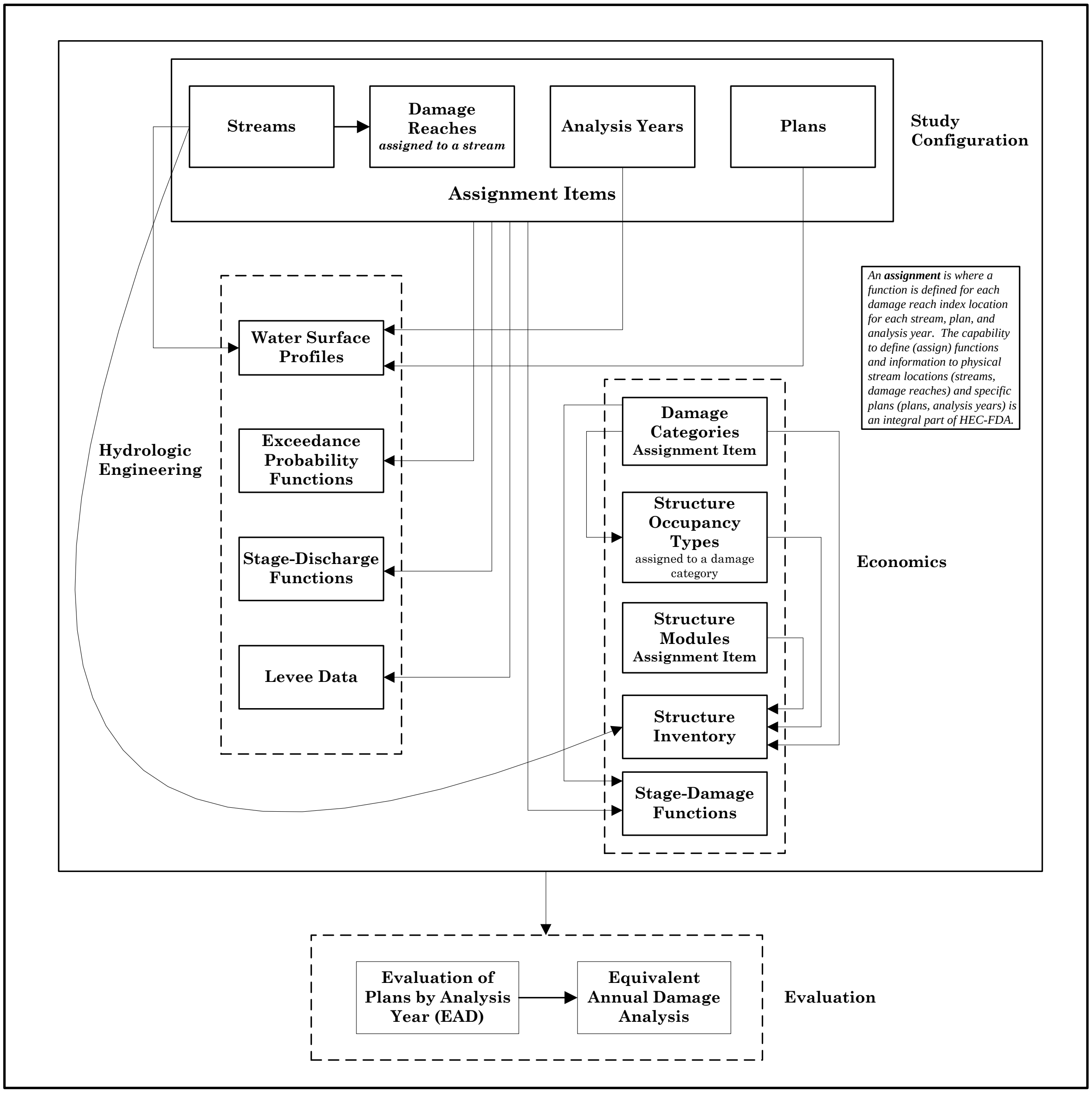

Figure 1 Relationship of Basic Data and Assignments

2.1.3 Model Outputs

HEC-FDA has several different types of output; most of this output is stored in database files, with some being saved to ASCII text files. For most of the input data, there is some form of output that is generated, since the model can generate a certain number of the functions (exceedance probability, stage-discharge, functions associated with a levee, and stage-damage functions). The output is displayed visually in the form of either plots or in a tabular format.

- Study Configuration Data – the output for this data is reports from the interface that list the entered streams, damages reaches, plans, and analysis years. For further details on output reports for streams, damage reaches, plans, and analysis years, see Chapter 3 of the Draft HEC-FDA User's Manual (November 2008).
- Water Surface Profiles– output for this data item includes a list of entered water surface profile sets, a plot and tabular report for an individual water surface profile set, and a report that lists what water surface profile set is assigned to a plan, analysis year, and stream. For further details on output reports for water surface profiles, see Chapter 4 (Sections 4.6, 4.7, 4.8, and 4.10) of the Draft HEC-FDA User's Manual (November 2008).
- Exceedance Probability Functions – if the user has chosen to create an exceedance probability function either from a water surface profile set, or from a statistical method, the generated probability function with uncertainty is displayed in the interface (results are saved to the database). Other available output is a list of all exceedance probability functions defined for a study, a plot and tabular report for an individual exceedance probability function, and a report that lists what exceedance probability function is assigned to a plan, analysis year, stream, and damage reach. For further details on output reports for exceedance probability functions, see Chapter 5 (Sections 5.5, 5.6, 5.7, and 5.9) of the Draft HEC-FDA User's Manual (November 2008).
- Stage-Discharge Functions – if the user has chosen to create a stage-discharge function from a water surface profile set, the generated stage-discharge function is displayed in the interface. Also, from the interface the user can calculate the uncertainty associated with a stage-discharge function which is also displayed in the interface (results are saved to the database). Other available output is a list of all stage-discharge functions defined for a study, a plot and tabular report for an individual stage-discharge function, and a report that lists what stage-discharge function is assigned to a plan, analysis year, stream, and damage reach. For further details on output reports for exceedance probability functions, see Chapter 6 (Sections 6.4, 6.5, 6.6, and 6.8) of the Draft HEC-FDA User's Manual (November 2008).
- Levee Data – for general levee data, the output consists of a report that lists the entered levees for a study, and a report that lists what levee is assigned to a plan, analysis year, stream, and damage reach. Other available output for a levee includes an exterior/interior relationship if defined, geotechnical probability of failure relationship if defined, and/or wave overtopping if defined. For each of these relationships the user can find output in the form of plots or tabular reports. For further details on output reports for levees, see Chapter 7 of the Draft HEC-FDA User's Manual (November 2008).
- Damage Categories – for damage categories output consists of a report that lists the entered damage categories for a study. For further details on this report, see Chapter 8, Section 8.2.5, of the Draft HEC-FDA User's Manual (November 2008).
- Structure Occupancy Type Data – output for structure occupancy type data includes a report that lists the entered structure occupancy types for a study, along with what damage category each structure occupancy type is assigned. Also, output available for each type of depth-percent damage function (structure, content, and other) consists of plots and tabular reports. For further details on output reports for structure occupancy types and depth-percent damage functions, see Chapter 9 of the Draft HEC-FDA User's Manual (November 2008).
- Structure Modules – for structures modules output consists of a report that lists the structure modules for a study, and a report that lists what structure module is assigned to a

plan and analysis year. For further details on output reports for structure modules, see Chapter 10 (Sections 10.5 and 10.7) of the Draft HEC-FDA User's Manual (November 2008).

- Structure Inventory – structure inventory output consists of a report that lists the entire structure inventory for a study, plus a report that lists for each structure the assignment of a damage category, structure occupancy type, stream, and structure module. If the structure has a specific depth-damage function (structure, content, and other) output also includes plots and tabular reports. For further details on output reports for structure inventory data, see Chapter 11 of the Draft HEC-FDA User's Manual (November 2008).
- Stage-Damage Functions – if the user has chosen to create stage-damage functions, the generated stage-damage function with uncertainty is displayed in the interface (results are saved to the database). Other available output is a list of all stage-damage functions for a study, a plot and tabular report for an individual stage-damage function, and a report that lists what stage-damage function is assigned to a plan, analysis year, damage category, stream, and damage reach. For further details on output reports for stage-damage functions, see Chapter 12 (Sections 12.4, 12.5, 12.6, and 12.8) of the Draft HEC-FDA User's Manual (November 2008).

The model also has output that is related to the results from the computations, these results are – Damage by Analysis Years (expected annual damage), Equivalent Annual Damage Analysis, and Project Performance. These reports are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management. Display of model results are consistent with technical procedures described in EM 1110-2-1619.

1) **Damage by Analysis Year Reports** – these reports display the results of the evaluation of plans by analysis year, and are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management plans; i.e., the results of expected annual damage (EAD) analysis. For further details on the Damage by Analysis Year Reports, see Chapter 14 of the Draft HEC-FDA User's Manual (November 2008). There are three groups of reports available:

   <u>General Information Reports</u> – the reports from this group provide information on what plans and analysis years were used for the computation of EAD (Data Management Summary), the Monte Carlo simulation by plan, analysis year, stream, and damage reach (Monte Carlo Analysis Summary), and warning information for each model compute (Warning Message Log). For the Monte Carlo Analysis Summary, output includes results in plots and tabular reports.

   <u>Damage Reach Summaries</u> – these reports provide information about the probability functions. These functions are the "average" curves from the Monte Carlo simulation and should not be used for analytical purposes. When the user requests the model not to compute EAD, then these reports are not available. There are four different types of probability function reports: discharge-probability, stage-probability, damage-probability, and damage reduced-probability. The output is by damage reach assigned to a specific plan, analysis, and stream, with results in plots and tabular reports.

   <u>Expected Annual Damage</u> – the expected annual damage reports provide information on the calculated EAD. There are four reports available for EAD: EAD by damage

categories; EAD damage reduced distribution; EAD by plans and analysis years, and EAD by analysis years.

EAD by Damage Categories – there are two reports, one report that displays the total damage by plans for a selected analysis year and the other report displays the total damage by damage reaches for a selected plan and analysis year.

EAD Damage Reduction Distribution - there are two reports, one report that displays the EAD for the without- and with-project conditions as well as the damage reduced for a selected analysis year. The report also displays the distribution of EAD reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25. The other report displays the EAD for the without- and with-project conditions as well as the damage reduced for a selected analysis year. The report also displays the distribution of EAD reduced by damage reach in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25.

EAD by Plan and Analysis Years – this report displays the EAD values for the base year and the most likely future year.

EAD by Analysis Years – this report summarizes EAD by damage reach for the based and most likely future years for a selected plan.

2) **Equivalent Annual Damage Analysis Reports** – these reports display the results of the equivalent annual damage computations, and are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management plans. For further details on the Equivalent Annual Damage Analysis Reports, see Chapter 15, Section 15.1, of the Draft HEC-FDA User's Manual (November 2008). There are two groups of reports available:

General Information Report – this report provides information on what plan were used for the computation of equivalent annual damage (Data Management Summary).

Summary Reports – these reports display the equivalent annual damage reduced and distributed (Reduced and Distribution), and equivalent annual damage by damage category (By Damage Categories).

Reduced and Distribution – there are two reports, one that displays the equivalent annual damage calculated for the without- and with-project conditions and the associated damage reduced by plan. Also, displays the distribution of equivalent annual damage reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25. The other report displays the equivalent annual damage calculated for the without- and with-project conditions and the associated damage reduced for a plan by damage reach. Also, displays the distribution of equivalent annual damage reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25.

By Damage Categories – there are two reports, one that displays the equivalent annual damage for individual damage categories by plan. The other report displays the equivalent annual damage for individual damage categories for a selected plan by damage reach.

3) **Project Performance Reports** – these reports display the information about the hydrologic/hydraulic performance of a plan. For further details on the Project Performance Reports, see Chapter 15, Section 15.2, of the Draft HEC-FDA User's Manual (November 2008). There are three types of reports available:

Target Stages by Damage Reach – this report lists target stages by damage reach and analysis year for a selected plan. The target stage is the stage at which a percentage of the specified event's damages occur. To ensure consistency with various damage reaches, the target stage is determined as the stage associated with the percent of residual damage of a specific exceedance probability event. That is the stage where 5% damage for the 1% chance exceedance event occurs. For levees or floodwalls without geotechnical failure, the top of the project (levee) is the target stage. For levees with geotechnical failure, there is no single value for the target stage and project performance is computed based on the joint probability of annual exceedance and probability of geotechnical failure. For damage reaches that don't have levees, target stage is the stage typically associated with the start of significant damage for the with-project conditions.

Project Performance by Damage Reach – this report displays the results of project performance by damage reach for a selected plan and analysis year. This report displays:

Target Stage Annual Exceedance Probability which is the median and expected annual exceedance probabilities associated with the target stage. The median value is computed from either discharge-probability and stage-discharge functions, or from a stage-probability function. The expected value is computed from results of the Monte Carlo simulation.

Long-Term Risk which is the probability of the target stage being exceeded at least once in a 10-, 30-, and 50-year period.

Conditional Non-Exceedance Probability by Events is the assurance of containing the specific .10, .04, .02, .01, .004, and .002 exceedance probability event within the target stage, should that event occur.

Project Performance by Plan and Damage Reach – this report displays the results of project performance by plan and damage reach for a selected analysis year. This report displays:

Target Stage Annual Exceedance Probability which is the median and expected annual exceedance probabilities associated with the target stage. The median value is computed from either discharge-probability and stage-discharge functions, or from a stage-probability function. The expected value is computed from results of the Monte Carlo simulation.

Long-Term Risk which is the probability of the target stage being exceeded at least once in a 10-, 30-, and 50-year period.

Conditional Non-Exceedance Probability by Events is the assurance of containing the specific .10, .04, .02, .01, .004, and .002 exceedance probability event within the target stage, should that event occur.

Finally, the model also has results that are not available through the model interface; these results are written to ASCII text files. The user must view these from outside of the HEC-FDA software.

1) Fda_EadTrace.out – this ASCII text file is created whenever a study is opened. The model will append debugging information to this file until the study is closed. This file contains debugging information that is useful only to program support people.

2) FdaResults.txt – when a report is displayed in the model an ASCII tab delimited file is also created for that report. This file enables the user to edit the file from another software program for formatting and inclusion in reports. All model reports are written to this file except for the general information reports. The model will append each report to this file until the study is closed. To view this file, since this is an ASCII text file the user can open this file with most word processing software packages, spreadsheet software packages, Notepad®, or WordPad®. To view with Notepad®, execute the Notepad® software, from the File menu, click Open, and browse to the study directory. From there open the FdaResults.txt file, see Figure 2 for the results.

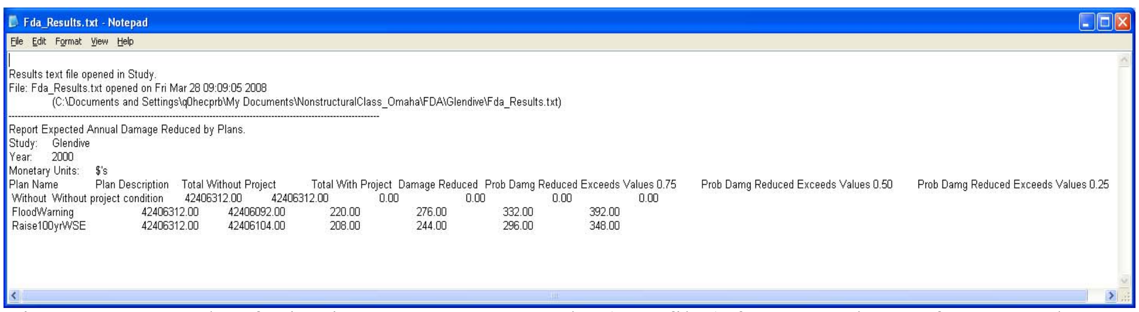

Figure 2 Example of Viewing HEC-FDA Results (text files) from Another Software Package

2.2 Model Components

The supplied version of HEC-FDA has been reviewed for technical quality by the HEC-FDA development team. The model was grouped by functions and applications under four headings, which may be considered to be the four key computational components or elements of the model. Each component area was then examined separately and specific technical quality tests were developed to examine the workings and processes within each one. The quality tests included testing the ability to input data; verifying that the computational engines of the model worked, and testing the output for correctness and the ability to view. These quality tests were run by the HEC-FDA development team. The four components of the model that were identified for technical examination are:

- Study Configuration
- Hydrologic Engineering
- Economics
- Evaluation

These components are described in more detail in the following sub-sections, and in further detail in the subsequent sections of this report which cover specific tests and investigations. Other aspects of the modes, such as hardware and software requirements, user interfaces, graphics displays, results, and supporting documentation have been subject to general usage rather than systematic testing for system quality and usability that has developed and evolved as the review and certification process progressed.

2.2.1 HEC-FDA Component One: Study Configuration

This component, Study Configuration, is where the physical study layout and the definition of the plans for analysis are configured for the study. This data is common for all analyses, and is built in a team environment, with the team agreeing on the study configuration. Data items under the study configuration are likely not to change during a study. Data includes streams, damage reaches, plans and analysis years.

Streams include various water bodies and are defined for the study, and therefore common for all plans and analyses. A study can have more than one stream, and a stream stationing convention must be adopted for the study. This stream stationing is used to define damage reach boundaries, damage reach index locations, water surface profiles, cross-sectional locations, and structure locations. Streams are defined by a name, with an optional description.

Damage reaches are specific geographical areas within a floodplain and are used to define consistent data for plan evaluations, and to aggregate structure and other potential flood inundation damage information by stage of flooding. Damage reaches are integral to both the hydrologic/hydraulic engineering and economic analyses. Delineation of damage reaches must be consistent with flood risk management measures; also, consideration needs to be consistent with exceedance probability function throughout the damage reach, and jurisdiction boundaries for reporting purposes. A damage reach is defined by assignment to a stream, a name, an optional description, a beginning station (downstream end), an ending station (upstream end), bank location (left, right, both), and an index location.

Plans are a set of one or more flood risk management measures or actions designed to operate over a period of time (project life). A plan is inclusive of the entire study area although it may have a flood risk management measure for a single damage reach. Plans are defined by a name, with an optional description.

An analysis year represents a static time period or year that the hydrologic/hydraulic engineering and economic data must be developed for analyses. Damage and project performance information are defined for each analysis year during the project life, such as the base year (first year of the plan operation) or most likely future year (development projection for a specific future year). The analysis year results are used to compute equivalent annual damage for a plan. Two analysis years are defined – base year and most likely future year, and then the most likely future year results are brought into current dollars with the defined interest rate.

2.2.2 HEC-FDA Component Two: Hydrologic Engineering

The Hydrologic Engineering component is where hydrology, hydraulics, and levee data are entered for the model analysis. Data includes: water surface profiles, exceedance probability functions, stage-discharge functions, and levee features. The water surface profiles are optional, but are recommended for model analysis. Profiles are required when computing aggregated stage-damage uncertainty functions at damage reach index locations. The water surface profiles must be consistent with discharge-probability and stage-discharge functions required for each plan, analysis year, stream, and damage reach.

A typical user setup for entering hydrologic engineering data would be:

1) A user would import the water surface profiles from either HEC-RAS or HEC-2. For analysis the water surface profiles must consist of eight flood events (.50-, .20-, .10-, .04-, .02-, .01-, .004-, and .002-exceendance probability flood events), and may be either discharge- or stage-based for each stream defined for the study. Stream stationing must be consistent with the damage reach and structure location stationing. A user can directly enter all of the water surface profile data directly into the model.

2) Next the user needs to define the exceedance probability functions that are required for analysis. In order to perform a flood damage analysis that considers flood events of all sizes, a relationship between flood magnitude and the probability of exceeding that magnitude is needed. This relationship is an exceedance probability function, which can be defined in terms of discharge or stage. An exceedance probability function can be either analytical or graphical (both of these terms are defined below). For either type, the user will also need to provide the equivalent length of record. For gaged areas, equivalent record length is the number of years of a systematic record of recorded peak discharges at the stream gage. For an ungaged location, the equivalent record length is estimated based on the overall "quality" of the exceedance probability function expressed as the number of years-of-record. The equivalent record length is very important because it is directly related to the uncertainty of the exceedance probability function.

   Analytical-Exceedance Probability Method – is used when a discharge-exceedance probability functions can be fitted by a Log Pearson Type III distribution. Analytical methods often apply for unregulated discharge-probability functions derived from stream gaged data or modeling. There are two methods of defining analytical discharge-probability functions; the default method is to enter the discharges for the .50, .10, and .01 exceedance probability events along with equivalent record length to compute synthetic statistics. The other method is to enter the Log Pearson Type III statistics – mean, standard deviation, skew, and equivalent record length.

Graphical Exceedance Probability Method – a graphical exceedance probability function is used when an exceedance probability function does not fit the Log Pearson Type III distribution. Typically this method is applicable for regulated flows, stage-exceedance probabilities, and partial duration functions. This method uses an approach termed order statistics. A graphical probability function is defined by specifying the discharge- or stage-probability ordinates and entering the equivalent record length. Ordered events are interpolated from the function based on the equivalent record length and error limit curves determined using order statistics. The final graphical probability function is based on mean or expected values defined by Weibull plotting positions along the curve. When entering data to define graphical probability functions, a number of data points should be used to describe the full range of the function. The ordered events method determines standard errors of points (estimates) along the curve from the relationship of each of the estimates to adjacent points and the slope of the function.

Transform Flow Relationship – for either an analytical or graphical exceedance probability function, this defines a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the exceedance probability function. This transform flow relationship could be the result of reservoir or channel routing, channel diversion, etc. It specifically allows for the isolation of the uncertainty related to the transforming mechanism, while maintaining the uncertainty of the discharge-probability function.

3) For each damage reach that has a discharge-probability function, a stage-discharge function needs to be entered, in order to transform the discharge in stage for each probability. The stage-discharge function should include enough points to define the function with the highest point representing the stage for 0.002 or 0.001 exceedance probabilities. Since the model does not extrapolate the stage-discharge function, a user should estimate a value or values for discharge (with uncertainty) that correspond to rare probabilities. The model will calculate a stage-discharge function based on water surface profiles if available.

4) For damage reaches that include a levee, you can specify levee size, failure characteristics, interior versus exterior stage relationships associated with the levee, or wave overtopping criteria. Following are the relationships that can be entered for a levee:

Exterior-Interior Relationship – the exterior-interior relationship defines the relationship between water surface stage on the river (exterior side of the levee) versus the stage in the floodplain (interior side of the levee). This relationship is necessary if the stage in the interior will not reach the same stage that is overtopping the levee or from interior drainage issues. This relationship must be developed from hydrologic or hydraulic analyses external to the model. If the relationship is not specified, the assumption is that the floodplain fills to the stage in the river for all events that result in stages that cause levee failure or are above the top of the levee.

Geotechnical Failure Analysis – this analysis is the relationship between water surface stage on the river (exterior side of the levee) versus the probability of levee failure. This analysis is used anytime the structural integrity of the levee is in doubt in other words, anytime the levee could fail prior to being overtopped. The geotechnical failure relationships are developed from geotechnical analysis according to existing geotechnical guidance.

Wave Overtopping - this analysis accounts for effects of wave overtopping when analyzing levees, floodwalls, or tidal barriers. For the model this analysis is a wave height versus a still water relationship. Another relationship for wave overtopping is the effective overtopping height and resulting interior stages. These relationships are developed outside of the model using wave overtopping analyses and overtopping volume versus interior stage characteristics.

2.2.3 HEC-FDA Component Three: Economics

The Economics component is where data entry and computations to produce stage-damage functions with uncertainty for flood risk management occurs. Data includes damage categories (need to define at least one), optional structure occupancy types, optional structure modules, optional structure inventory, and stage-damage functions. A typical user setup for entering economic data would be:

1) Create damage categories (maximum of twenty), enough to facilitate detailed reporting. Damage categories are used to consolidate large number of structures into specific categories with similar characteristics for analysis and reports. The model calculates stage-damage on a structure-by-structure basis and aggregates the result for each structure to an index location. Typical damage categories are: residential, commercial, industrial, open space, and public facilities.

2) For each defined damage category, enter structure occupancy type information, however, structure occupancy types are not required. A structure occupancy type describes a class of structures (e.g., single family, no basement, raised foundation, one story) and is a subcategory of a defined damage category. Data entered for a structure occupancy type includes:

   Depth-Percent Damage Functions – a depth-percent damage function represents the damage caused to a structure, the contents of a structure, and "other" (other can be used to compute damage for any other item not accounted for in structure or content value, e.g., automobiles) for given depths of flooding at a structure. The damage is based on a percentage of the total value of the structure, content, and "other" respectively. The percent-damage is multiplied by the structure value, content value, or "other" value to get a unique depth-damage function at the structure. Depth-percent damage functions should always contains a zero damage depth, and negative depths are acceptable. The uncertainty associated with the depth-percent damage function is entered by ordinates based on the specified distribution.

   USACE has provided guidance for using generic depth-percent damage functions in flood risk management studies, which is outlined in EGMs 01-03 and 04-01. These are standardized relationships for estimating flood damage and other costs of flooding, based on actual losses from flood events. These functions calculate content damage as a percent of structure value rather than content value. Using these functions within

HEC-FDA requires close attention in specifying a content-to-structure value ratio. Refer to the aforementioned EGMs for further details.

Content to Structure Value Ratio – this value is used to estimate the total content value if the structure inventory does not include content value information. The content to structure value ratio is the numeric value, in percent, that represents the content value divided by the structure value for a particular structure occupancy type. The computed content value is then used to proportion the contents depth-percent damage function.

Other to Structure Value Ratio – this value is used to estimate total value of the property represented by other if the structure inventory does not include other value information. The other to structure value ratio is the numeric value, in percent, that represents the maximum other value divided by the maximum structure value for a particular structure occupancy type. The computed content value is then used to proportion the other depth-percent damage function.

Uncertainty Parameters – distributions or uncertainties that are associated with estimating the depth-damage functions, structure values, content value ratios, other value ratios and first flood stage. These are used to develop the total aggregated stage-damage-uncertainty functions by damage categories for a damage reach. These parameters include:

First Floor Stage – the standard deviation in feet (meters) of the uncertainty in the first floor stage estimate of a particular structure occupancy type. This value is based on the procedures/type of surveys used to estimate the first floor stage.

Structure Value – the error associated with structure value is entered as the standard deviation, in percent of structure value, associated with the uncertainty in the structure value estimate for a particular structure occupancy type.

Content/Structure Value – the standard deviation is a percent of the content to structure value ratio. It is associated with the error in estimating the ratio. For example, for a content to structure value ratio of fifty percent, an entered standard deviation of ten percent would mean that the plus/minus one standard deviation range is forty-five to fifty-five percent. When using the generic depth-damage relationships, do not enter a content/structure value.

Other/Structure Value – the standard deviation is a percent of the "other" to structure value ratio. It is associated with the error in estimating the ratio. For example, for a "other" to structure value ratio of fifty percent, an entered standard deviation of ten percent would mean that the plus/minus one standard deviation range is forty-five to fifty-five percent.

3) Create structure modules and assign to a plan and analysis year group. Structure modules allow the user to vary one or more structure characteristics by plan and year or to include or exclude one or more structures from a plan/year. Data entered for structure modules are a name and an optional description. There is a default structure module (Base) and any

new structure is automatically assigned to the default structure module. Structure modules must be defined prior to development of a structure inventory.

4) If a study includes a structure inventory the user needs to enter or import a structure inventory. Structure inventories are a record of the attributes of unique or groups of structures relevant to flood risk management analysis. The inventory is used to compute an aggregated stage-damage function by damage category at the damage reach index location station. Required structure attributes include: the name for the structure; stream station; stream; bank designation; structure value; occupancy type; structure module; and structure stages associated with ground or first floor. Optional attributes include: content value; other value; address; coordinates (highly recommended); notes; an image; and additional structure stages for basement type flooding. Structures are assigned to a specific damage category, structure occupancy type, stream, and structure module. The structure module is used to specify which plans and analysis years the structure will be used for damage analysis. The user can enter data directly or import a structure inventory.

5) The final step for this component is the creation of stage-damage functions, which can be entered, calculated by the model, or imported. USACE defines a stage-damage function as the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given river or damage reach. From the model the user can enter stage-damage functions manually or the model will calculate stage-damage functions. For the model to compute stage-damage functions the program requires the following information and the uncertainty about that information: depth-percent damage functions, first floor elevations, and structure and content values. In addition, a complete set of water surface profiles (eight profiles) must be available. Additionally, it is a good idea to have discharge exceedance probability functions and stage-discharge functions for the stage-damage function computations. For the model a complete set of stage-damage functions for all categories, damage reaches, and streams must be entered to analyze a specific plan for an analysis year. The uncertainty is defined only by the normal probability density function. If there is no uncertainty, the user must select the normal distribution and enter zeros for the standard deviations – don’t leave the uncertainty field blank.

2.2.4 HEC-FDA Component Four: Evaluation

The Evaluation component is where a user may review the study status, perform two types of analyses, and view results. The two analysis options are: 1) computation of expected annual damage and project performance (Evaluation of Plans by Analysis Year), and 2) computation of equivalent annual damage over the specified analysis period (project life) for the plan. In general, data developed and displayed under hydrologic engineering and economics represent the best estimates of the median values of the exceedance probability, stage, and damage functions for without- and with-project conditions. Uncertainty parameters of the functions are also developed for study conditions. The analyses performed and results displayed use the median valued functions and associated uncertainties as input to produce expected values as output. The computational procedure used is Monte Carlo.

1) **Evaluation of Plans by Analysis Year** – computation of expected annual damage (EAD) is the first step in the overall computation process. The model combines the exceedance probability functions, stage-discharge functions, and structure inventory data to compute EAD. Plan and damage reach project performance analyses are based on target standards defined for without-project conditions for the study. There are three different cases for determining the target:

    a. For reaches without levees, the target is based on an estimate of the stage at which significant damage begins for the without condition,
    b. For reaches with a levee that have no geotechnical failure, the target is the top of levee stage, and
    c. For reaches with a levee that have geotechnical failure, the target is based on both the annual exceedance probability and the probability of failure.

    For reaches without levees, the standards used by the model are based on the residual damage associated with a specific exceedance probability event. Performance targets are essentially the zero damage stage but normally consider minor damage to the infrastructure as acceptable and significant damage to structures as not acceptable. Consistent criteria for comparing the impacts of different measures and plans are also a goal. Experience at HEC has shown that a 5 percent residual damage associated with the .01 exceedance probability event is normally a good target stage and was adopted as the model default. The user may enter other values if they are deemed better for study conditions. The same values must be used for all calculations.

2) **Equivalent Annual Damage Analysis** – the next step in the compute process is the computation of equivalent annual damage. The expected annual damage computation for the base and most likely future conditions of a plan must be successfully computed before you can compute equivalent annual damage analysis. The flood damages associated with a plan are calculated in average annual equivalent terms. The procedures discount the expected annual damage to the beginning of the period of analysis or the base year. Future year damage values are linearly interpreted between the base and most likely future year conditions and assumed constant from the most likely future year to the end of the analysis period. The analysis period (project life) is the period of time over which the plan has significant beneficial or adverse effects. It is normally fifty years and is not to exceed 100 years.

2.3 Externally Generated Input Datasets

A feature of HEC-FDA is that in addition to the calculations and formulae which comprise the model, it can take advantage of data from external sources. Water surface profiles sets can be imported from both HEC-2 (Water Surface Profiles, USACE, 1991) and HEC-RAS (River Analysis System, USACE, 2002). Both pieces of software export to an ASCII file, which the model can then import. Most structure inventories are built outside of the model, and are usually stored in some sort of database. Most of these databases allow the exporting of the structure data to ASCII files or in the form of a Microsoft Excel® workbook. Once again, the model can then import the data from an ASCII file.

The USACE Hydrology, Hydraulics and Coastal Community of Practice (HH&C CoP) is the group responsible for addressing the technical subjects of hydrology, hydraulics, and coastal engineering. This group has recommended HEC-RAS as a piece of software for conducting hydraulic studies, and HEC-HMS (Hydrologic Modeling System) as a piece of software for conducting hydrology studies. Both pieces of software have been accepted by the HH&C CoP to provide input to HEC-FDA.

2.4 Model Development Process

A provisional version of HEC-FDA was released in December 1996. This version of the model was released to specific USACE District and Division offices for testing and review. HEC was provided with an extensive list of updates and error fixes. Changes were made, and HEC conducted more in-depth testing. Version 1.0 of the model was released in January 1998 as the first general release of the model. Another updated version (1.1) was released in September 1999.

Version 1.2 of the model was released in March 2000, once again based on comments from users; changes were made to the model. Fixes were as follows:

- Project Performance Reports - the current version of HEC-FDA is reporting the 0.75% event conditional stage for the 1% event conditional stage. A fix has been made which corrects this problem, since the 1% event exceedance can be used for levee certification this fix could impact district results for levee certification.
- Negative Stage Values - a fix for entering negative stage values associated with a graphical stage-exceedance probability function was made.
- Flat Damage-Exceedance Probability Functions - the HEC-FDA program uses the discharge-exceedance probability, stage-discharge, and stage-damage functions to compute a damage-exceedance probability relationship during the calculation of expected annual damage (EAD). If the damage-exceedance probability function is flat, such as the result of regulated flows or flat terrain, the program reports an error. A fix was made to correctly handle a flat damage-exceedance probability function.
- Study Water Surface Profiles - removed a warning message from this dialog.

The current version (1.2.4) of the model was released in November 2008. Once again based on comments from users, changes were made to the model. Fixes were as follows:

- Increased the number of maximum damage categories from nine to twenty.
- Project performance reports, there is greater accuracy in the calculation of the median and mean annual exceedance probabilities.
- A damage reach may contain both a geotechnical failure function as well an interior-exterior stage function; previously, a damage reach could contain either one but not both
- A change has been made in the calculation methodology for "average" probability functions; although these are not used in the calculation of expect annual damage (EAD), they do indicate an "average" curve based on those generated during the Monte Carlo simulations.

- The algorithm for computing EAD and project performance whet her is a geotechnical failure has been changed. The calculations give greater accuracy in the results within the failure zone when the difference in elevation is small between the probability of failure (PFP) and probability of non-failure points (PNF). However, if the difference in elevation between the PFP and PNF points is large, the user must enter enough points in the geotechnical failure curve to adequately define the probability function in that range. Version 1.2.4 uses the points from the geotechnical failure curve in the geotechnical failure range as the calculation points rather than the possibly more detailed internal calculation points that otherwise would be used.
- When computing stage-damage for structures that have a depth-direct dollar damage function, the price index is now applied to the dollar amounts; previously, the direct dollar values were not adjusted by the price index.
- Graphical discharge-probability and stage-probability functions are stored both in binary fields and in a memo field in tab-delimited format. Likewise, the transform flow function is stored in a memo field as tab-delimited data. The data in the tab-delimited memo field is used in calculations and can be edited using dBASE or MS Access.
- The mean and median annual exceedance probabilities (AEPs) are stored with five rather than three digits to the right of the decimal point.
- For Log Pearson Type III discharge-probability functions, calculations are carried out to an exceedance probability of 0.0001 for greater accuracy in the project performance calculations.
- When water surface profiles are imported as a delimited text file, you can now import a large number of cross-sections (constrained only by XBase memo field limits). Previously, you could correctly import a maximum of ~1,000 cross-sections from a delimited file. HEC-FDA has been tested for importing a stage-probability water surface profile set with 100,000 cross-sections. However, it is very slow to display the profile input dialog.
- It is now allowable to have negative stages in input stage-probability functions.
- For Log Pearson Type III discharge-probability functions, the confidence limits are now computed for the 25% and 75% limits. They previously computed at +1 and -1 standard deviations but were labeled as 25% and 75%
- The equivalent annual damage is calculated properly when the most likely future year is beyond the period of analysis.
- A fix for the importing of water surface profiles and all assignments.
- For stage-probability functions which have a steep slope in the function followed by a very flat slope for rare exceedance probabilities, FDA Version 1.2.4 will use the calculated uncertainty about the flat portion of the function in the expected annual damage (EAD) and project performance computations. However, when viewing stage-probability functions from the FDA graphical user interface (GUI), either graphically or in a report, FDA will incorrectly display greater uncertainty about the flat portion of the function.

2.5 Model Capabilities and Limitations

HEC-FDA does sampling by function, which is required to compute net benefits and damage reduced, along with distribution of EAD. The model incorporates two USACE approaches to flood risk management analysis – consistency with scientific understanding and a reasonable risk analysis procedure.

During the review of an earlier version of ER 1105-2-101 (Risk Analysis for Flood Damage Reduction Studies), a review of HEC-FDA version 1.2 was also performed by the Water Science and Technology Board, National Research Council (NRC) in 2001. The NRC developed a list of limitations (Table 1), some of which have not been addressed in version 1.2.4. The NRC felt that the model provided explicit quantification of engineering and economic uncertainties which lead to better projects, provides new techniques which are a significant step forward, and by replacing the former levee freeboard approach, the model provides more consistent results.

A workshop on Flood Damage Reduction Analysis was held over a three-day period (6-8 February 2007) at HEC. Participants included personnel from HEC, the Institute of Water Resources (IWR), and two participants from the Dam and Levee Safety Certification Group. The purpose was to discuss the direction of flood damage reduction (FDR) analyses within USACE for the short and long term. During discussions, limitations of HEC-FDA were provided by the participants and are as follows:

- the model should compute using an event-based analysis, along with- and without-project conditions (also an NRC recommendation)
- remove price index, and use an economic update plan
- systems approach instead of the current system/component specific approach; this will better define, estimate, and combine uncertainties
- agricultural damages and uncertainties
- uncertainty about the geotechnical probability of failure curve or the fragility curve
- cost and its associated uncertainty (using MCACES methodology) needs to be added to the model

Each of these issues is being reviewed and consideration is being given to possible implementation in future versions of HEC-FDA. None of these issues should prevent the current version of HEC-FDA from being certified as they are possible enhancements not corrections to the current capability of the model.

Table 1
National Research Council Recommendations

NRC Comment	USACE Comments & Actions
Risk Measures & Modeling	
NRC Comment	**USACE Comments & Actions**
Too many types of engineering performance measures to be understood by citizens.	Concurs; annual exceedance probability (AEP) & uncertainty is calculated by the model.
Conditional non-exceedance probability (CNP) is difficult to understand.	Concurs; USACE will use internally, but will change to assurance.
Quantify each source of uncertainty and properly incorporate uncertainty in analysis.	Concurs; as methods mature, a more complete representation of all uncertainties will evolve; no change to model at this time.
Better define, estimate, and combine uncertainties.	Partially concurs; investigations to define improved approaches will be conducted and implemented; systems approach identified for R&D.
Reduce variation in estimates of water surface profiles.	Concurs; ongoing hydrology and hydraulics activity.
Identify which uncertainties are more important.	Partially concurs; determine if key variables used in risk analysis need to be expanded or modified.
Will Monte Carlo become impractical?	Non-concurrence, Monte Carlo is adequate.
Conduct ex post studies to identify failure modes.	Concurs; need to provide resources to examine projects under field conditions.
Monte Carlo should be performed on a spatial scale.	Partially concurs; compare aggregate reach approach and total system approach; need R&D funds; need to evaluate; probably not easy.
Correlation of random variables should be introduced.	Partially concurs; identify potential correlated variables and assess their importance; need R&D funds; need to evaluate; probably not easy.
Geotechnical Reliability	
NRC Comment	**USACE Comments & Actions**
Evaluate levee as a spatially distributed system.	Concurs; continues to improve this process; conceptually being addressed with PRA program; needs R&D funds.
Conduct ex post studies to identify levee failure modes.	Concurs; provide resources to examine projects under field conditions.
Use the updated geotechnical approach.	Concurs; already added to model.
Natural variability and knowledge uncertainty should be treated differently in Geotechnical modeling.	Concurs; analysis model continue to improve, no action at this time.
Consider flood duration for geotechnical reliability.	Concurs; analysis model continue to improve, no action at this time, but is an on-going effort.
Hydrologic Analysis	
NRC Comment	**USACE Comments & Actions**
Approximation used to generate mean and standard deviation for an LP3 distribution based on expected probability adjustment in 17B has no theoretical justification.	Non-concurrence; develop an estimation methodology which considers the estimation uncertainty in all the LP3 parameters. Methodology needs to be approved by interagency work group on flood frequency analysis; This issue has been debated in the professional literature for twenty years. USACE will continue to follow the established Federal interagency policy.
Can't ignore large uncertainty in skew.	Concurs; investigate method to include skewness uncertainty, and incorporate in analysis methodology as time and resources permit.
Compare synthetic rainfall to observed records to compare error.	Partially concur; will be studied as resources permit; H&H should perform with new R&D funds.
H&H should be randomized at scale of river reach rather than damage reach.	Partially concur; compare aggregate reach approach and total system approach; need R&D funds; need to evaluate; probably not easy.
Economics	
NRC Comment	**USACE Comments & Actions**
Analysis is incorrect because it aggregates structures.	Partially concur; unclear if USACE approach is in error; should evaluate; needs R&D funds; probably not easy.
Analysis ignores the interdependence or correlation among distributions.	Partially concur; real issue is correlation of damage between reaches; should evaluate; needs R&D funds; probably not easy.
Correlation between structure and content value and correlation errors in first-floor elevations of structures at different locations.	Partially concur; identify potential of correlated variables and assess their importance; not sure USACE method is incorrect but willing to test; should evaluate; needs R&D funds; probably not easy.

Table 1 (continued)
National Research Council Recommendations

Economics (continued)	
Summation made over values at the damage reaches assumes that damage reaches are perfectly correlated.	Partially concur; real issue is correlation of damage between reaches; should evaluate; needs R&D funds; probably not easy.
Randomize structures jointly.	Partially concur; identify potential of correlated variables and assess their importance; not sure USACE method is incorrect but willing to test; should evaluate; needs R&D funds; probably not easy.
USACE focus is on uncertainty in damages not uncertainty in benefits.	Partially concur; should investigate computing uncertainty in damage reduced (benefits); should evaluate; needs R&D funds; probably not easy.
Consistent Terminology	
NRC Comment	**USACE Comments & Actions**
Adopt consistent terminology.	Concurs; updated guidance (ER 1105-2-101); EC 1110-2-6067 is being created.
Uncertainty should be used to describe situations without sureness.	Non-concurrence; USACE feels this is appropriately defined.
Define natural variability vs. knowledge uncertainty.	Partially concurs; academic interest only, no action at this time.
Adopt "risk analysis" terminology.	Concurs; updated guidance (ER 1105-2-101); EC 1110-2-6067 is being created.
Levee Certification	
NRC Comment	**USACE Comments & Actions**
Levee certification criterion is deficient.	Partially concurs; procedure negotiated with FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
USACE should set a single conditional non-exceedance probability for levee certification.	Initiate discussions with FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Certification criteria shall provide a uniform level of flood protection, e.g. the median level historically provided (1/230).	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Examine a large number of FDR projects to determine median annual exceedance probability.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Develop a table showing percentiles of variability in the annual exceedance probability of its FDR projects.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Maintain an inventory of past projects of the amount of freeboard provided and resulting level of protection.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Criterion for certifying a levee should be that it provides adequate protection against failure of the FDR system.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Floodplain Management	
NRC Comment	**USACE Comments & Actions**
FDR projects should explicitly address social values.	Concurs; separate part of planning process; USACE recognizes the value if incorporating into risk analysis; major effort to bring life safety into process.
Risk analysis should consider non-structural alternatives.	Concurs; presently included in model as appropriate; could address with new research money from FCSDR.
NRC Comment	**USACE Comments & Actions**
Quantify ecological, health and social effects of FDR projects.	Concurs; currently USACE practice but not a risk issue; USACE is pursuing risk informed planning and decision making.
Goal of floodplain management is to use the land for greater social benefit.	Concurs; currently USACE practice but not a risk issue; USACE is pursuing risk informed planning and decision making.
Risk Communication	
NRC Comment	**USACE Comments & Actions**
Risk assessment should involve stakeholders.	Concurs; works with local sponsors; holds public meetings and workshops; USACE is pursuing risk informed planning and decision making.

SECTION 3

Model Evaluation

3.1 Certification Criteria

In accordance with PMIP protocols and EC-1105-2-407, HEC-FDA is subject to a Level 4 certification/review. The model was reviewed on the basis of technical quality, system quality and usability. A description of the certification criteria, based on the PMIP model certification protocols is presented in the remainder of Section 3.1.1 through 3.1.3. Section 3.2 presents an overview of approach to model testing, including the selected approach for HEC-FDA.

The current version of HEC-FDA utilizes inputs generated in accordance with the established protocols and engineering models as the starting point for HEC-FDA and these are considered to be external model components. A detailed assessment of applicable components of HEC-FDA with respect to each of the certification criteria and discussion of significant observations during the review is presented in Sections 3.3 through 3.5. A summary of basic certification criteria outlined in the PMIP Protocols and the corresponding assessment of HEC-FDA is provided in Section 4.1.

3.1.1 Technical Quality

Analytical tools and models used to support flood risk management analysis are expected to be based on established contemporary scientific theory. The study area and how it responds to the influences that act upon it must be realistically represented by the model's components, in the form of calculations based on the application of scientific theory. The analytical requirements of the model must be identified, and the model must address these requirements. Formulas and calculation routines that form the mechanics of the model must be accurate and correctly applied, with sound relationships between variables. The model should also be able to reflect the influences or restrictions of man-made laws, policies, and practices. The model should be logically unassailable and all assumptions, whether they pertain to natural or human-induced processes, must be valid and documented. Technically correct models with rational assumptions should produce robust, reproducible results that stand up to the rigorous scrutiny in later stages of the plan formulation process.

3.1.2 System Quality

System quality refers to the entire system used for model development, use and support, including software and hardware requirements, and data interoperability or compatibility with other systems. Efficiency and operation stability of the model have also been considered under system quality criteria. Factors such as the appropriateness of the software or programming language, correctness of programming, and availability and quality of supporting software and hardware can be considered in the assessment of system quality. The ability to import model data and/or output into other software analysis tools is another factor associated with system quality.

3.1.3 Usability

Usability refers to the overall ease and efficiency with which users are able to operate the model to obtain the relevant information required to support decisions made in the planning of flood risk management studies. The issues that can be considered during this component of the certification include:

- User friendliness of the model, including logical configuration and intuitiveness
- Availability and quality of supporting model documentation
- Availability of training and technical support for model users
- Ease of access in obtaining input data required to run the model
- Availability of the model programs or files to potential users
- Ability to extract understandable, relevant information from model outputs

3.2 Approach to Model Testing

The approach used in the review of HEC-FDA varied according to the individual assessment criteria under review. While the technical quality assessment proceeded principally according to a series of specific tests concentrating on distinct inputs, functions or calculations, the assessment of usability and to a large extent that of system quality have been based on observations drawn from the general use and operation of the model. These tests have been conducted manually by the HEC-FDA development team and include testing the usability of the model and testing the graphical user interface for various standards defined for effective and efficient usage and accessibility. Also, tests were run to verify results from computation of the model.

The version of the model subject to review and testing was made available for download as of November 2008 from http://www.hec.usace.army.mil as instructed by the developers. More details regarding the model version and installation issues are presented in Section 3.4. From the same source two data sets were obtained which the HEC-FDA development team has used as the primary test bed for the development of the model. The Beargrass Creek study, in Louisville, Kentucky, consists of two highly urbanized damage reaches on the South Fork Beargrass Creek, which drains a total of about sixty-one square miles. The study also included the Buechel Branch, which has five damage reaches on it, with fifteen damage reaches along the South Fork Beargrass Creek. The flood risk management features to be analyzed are detention storage and floodwalls alone and in combination. The other data set that was provided is the Chester Creek watershed located near Philadelphia, Pennsylvania, which drains 177 km^2 area. For this data set, simulated project analysis is performed to determine feasibility of implementing several flood risk management plans.

3.3 Technical Quality Assessment

As discussed in Section 3.1.1, the technical quality assessment examined the model's ability to realistically represent conditions in the study area, and response to various flood risk management plans.

The testing approach used in the technical review of HEC-FDA was not intended to be absolutely comprehensive. Due to the complexity of the model not every constituent function, application, or calculation could be fully explored within the constraints of time and budget. The model and supporting documentation were reviewed and examined, and selected elements were identified for systematic testing, using the Beargrass Creek and Chester Creek data sets that are available with the current version of the model. As the review and testing process evolved, further issues and areas for closer review were identified and examined in more detail.

In general, the method used to test for technical quality was to configure the model so as to isolate individual variables, applications or processes identified for assessment, and then to modify the simulation conditions or other inputs so their response could be monitored. A number of issues were identified following examination of outputs from scenarios and simulations already specified within the reviewed version of the model. In some cases manual calculations were performed to confirm the processes involved and their accuracy of application. Some tests involved the input of technically irrational or erroneous data, in order to test the ability of the model to recognize input which may be the result of user error or faults in externally sourced data, and the ability of the model to prompt the user to revise it, as appropriate. The overall technical quality assessment also included considerations of the extent, clarity, and quality of data outputs.

3.3.1 Technical Quality Assessment of Component One – Study Configuration

As discussed in Section 2.2.1, the Study Configuration component of the model is where the physical study layout and the definition of the plans for analysis are configured for the study. This data is common for all analyses and is not likely to change during a study, and includes streams, damage reaches, plans, and analysis years. Testing for this component included testing the usability of the model and testing the graphical user interface for various standards defined for effective and efficient usage and accessibility. Currently, the model only allows two analysis years (Base Year, Most Likely Future); this does not prevent the model from being used, but is a limitation.

3.3.2 Technical Quality Assessment of Component Two – Hydrologic Engineering

As discussed in Section 2.2.2, the Hydrologic Engineering component of the model is where hydrology, hydraulics, and levee data are entered for the model analysis. This data is required for model analyses, and includes water surface profiles, exceedance probability functions, stage-discharge functions, and levee features.

- Water Surface Profiles Sets

  A water surface profile set in the model is the stream water surface stage along a stream length associated with discharge values of eight flood events. The default eight flood events are for the .50-, .20-, .10-, .04-, .02-, .01-, .004-, and .002-exceedance probability flood events. The model requires eight flood events; but the model does allow changing the probability designations. Each water surface profile set has stream stations, invert elevations, and discharge and stage values. The stage and discharge values have to increase by profile at one or more cross sections. Most water surface profiles sets are imported from HEC-RAS or HEC-2. Water surface profile sets can be used to develop discharge-probability and stage-discharge functions at an index location station within a damage reach, which ensures consistency of data. Also, a water surface profile set can be used in the creation of stage-damage functions (see Section 3.3.3).

  When developing an analytical-exceedance probability function (using Bulletin 17B procedures) for a particular plan, analysis year, stream, and damage reach, the model will use the water surface profile set for that particular plan, analysis year, and stream, and retrieve the discharge values for three exceedance probabilities - .50, .10, and, .01. The user enters an equivalent record length, saves the information, and the model will compute the analytical-exceedance probability function with uncertainty.

  The model will create a graphical exceedance probability function by retrieving the eight discharge-exceedance-probability data points from a water surface profile set for a particular plan, analysis year, stream, and damage reach. This creates a function with eight probability events, the statistics, including the uncertainty are influenced by the entire sample. Consequently the entire range of the function should be defined including an annual return 1-year event (0.999) estimated value. So the user will need to add an addition point at the 0.999 (1-year) event, along with the equivalent record length. Once the information is saved, the model will compute the graphical exceedance probability function with uncertainty.

  To create a stage-discharge function from a water surface profile set for a particular plan, analysis year, stream, and damage reach, the model will retrieve nine ordinates from the water surface profile set, this includes the invert stage (zero discharge) and the eight stage-discharge values. The model will automatically create a nine-point stage discharge function at the damage reach index location. To add uncertainty the user will need to select an uncertainty type (None, Normal, Triangular, Log Normal) or the user can have the model calculate the uncertainty by defining an uncertainty for a specific stage.

- Exceedance Probability Functions

  In order to perform a flood damage analysis that considers flood events of all sizes, a relationship between flood magnitude and the probability of exceeding that magnitude is needed. This relationship is an exceedance probability function, which can be defined in terms of discharge or stage. An exceedance probability function can be either analytical or graphical. For either type, the user will also need to provide the equivalent length of record, which is the number of years of a systematic record of recorded peak discharges at a stream gage.

In the model an analytical discharge-exceedance probability function is computed according to procedures described in Bulletin 17B. The computational procedure is either based on either entering information for Log Pearson Type III or an algorithm that the model labels "Compute Synthetic Statistics". This algorithm (default method) is used if the statistical parameters are unknown, such as at ungaged locations. The computed function should be compared with the original known discharge-exceedance probability function or with the water surface profile data by using the plot options provided in the model. If this method does not produce a function that closely matches the original known function, the graphical method should be used.

In the model a graphical exceedance probability function (discharge- or stage-exceedance probability) is defined by specifying the mean discharge- or stage-exceedance probability ordinates and the equivalent record length that describe the known function. The graphical discharge- or stage-exceedance probability function should be based on mean or ordinate expected values (such as an eye-fit curve through Weibull plotting positions). Once specified, ordered events are interpolated from the function based on the equivalent record length and error limit curves determined using order statistics. The distribution of errors is assumed to be normal about the specified function. A plot or report (tabulate) of the function and error limit curves can be created (see ETL 1110-2-537).

A flow transfer relationship may be used to define a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the discharge- exceedance probability function. The relationship is entered as x-y paired data in ascending order. Uncertainty of the dependent variable (regulated flow) is also defined. The distribution type and the distribution parameters are entered for each point on the flow transfer function.

- Stage-Discharge Functions

The stage-discharge (rating) function with uncertainty specifies the median stage-discharge functions to be used for a specific plan, analysis year, stream, and damage reach in the evaluation of flood risk management measures. The same median stage-discharge functions may be used for several plans and analysis years but not different streams or damage reaches. If water surface profiles are defined for the specified damage reach, the model will compute a nine-point stage-discharge function from the water surface profile data.

The associated uncertainty of a stage-discharge function is defined by specifying the error distribution type and entering the appropriate data for each ordinate (stage). The error distribution may also be calculated based on parameters specified for a specified stage. The uncertainty will be computed by linear interpolation between zero (at the invert stage) and the specified uncertainty and stage. The uncertainty will remain constant for ordinates greater than the specified value. The uncertainty can be defined as having a normal, log normal, triangular, or a uniform distribution.

- Levee Features

In the model, levee features include top of levee stage, failure characteristics, interior versus exterior stage relationships, or wave overtopping criteria is specified. The levee, floodwall, or tidal barrier characteristics are entered and other relationships are defined depending on whether the levee is subject to geotechnical failure or wave action (overtopping) which may cause flooding (see EM 1110-2-1619, ETL 1110-2-547, ETL 1110-2-328, and ETL 1110-2-546).

The exterior-interior relationship defined in the model is a relationship between the water surface stage on the river or exterior side of the levee versus the stage in the floodplain or interior side of the levee. This relationship is necessary if the stage in the interior will not reach the same stage that is overtopping the levee or from interior drainage issues. This may be due to floods that result in stages near the top of the levee overtopping as designed in a safe, controlled manner, or a flood hydrograph volume not sufficient to fill the floodplain to the stage equal to the top of the levee. In either case, the relationship must be developed from hydrologic or hydraulic analyses external to the model. If the relationship is not specified, the assumption is that the floodplain fills to the stage in the river (represented by the exterior stage-discharge function for the reach) for all events that result in stages that cause levee failure or are above the top of levee.

Geotechnical failure analysis is the relationship between water surface stage on the river or exterior side of the levee versus the probability of levee failure. This feature is used anytime the structural integrity of the levee is in doubt, i.e., anytime the levee could fail prior to being overtopped. The geotechnical failure relationships are developed from geotechnical analysis according to existing geotechnical guidance. The geotechnical failure relationship is a combined probability of levee failure relationship and includes failure modes such as under seepage, slope stability, through seepage, surface erosion, etc. At this time, uncertainty about the geotechnical failure relationship is not available.

Wave overtopping analysis in the model accounts for the effects of wave overtopping when analyzing levees, floodwalls or tidal barriers. The purpose is to account for damage in the floodplain due to waves spilling over the top of new levees or floodwalls and to account for waves when considering levees subject to failure.

New Levees and Floodwalls - generally, by design, are not subject to failure below their crest. These structures can be subjected to wave action from large rivers, estuaries, or in coastal areas. If wave action is shown to cause flood inundation damage, a wave overtopping analysis may be warranted. The model includes a simplified approach to evaluate damage caused by wave overtopping.

A still water level versus wave height relationship needs to be entered. Still water stage corresponds to the exterior stage discharge or stage frequency function specified for the damage reach. The still water versus wave height relationship and uncertainty are developed outside the model from historical data and statistical analysis or by some other method. If there is uncertainty associated with the wave height, select the appropriate uncertainty type (None, Normal, Triangular, Log Normal), and then enter the parameters for the uncertainty for each wave height.

When a levee or floodwall is subjected to wave action, a portion of the wave may overtop depending on whether the wave strikes the structure. The volume of water that spills over the levee or floodwall is dependent on the effective overtopping height. Overtopping is only available if geotechnical failure relationships have not been defined for the levee. The relationships that define the overtopping parameters are developed outside the model from known wave characteristics and hydraulic analyses. The following describes how the wave height and the overtopping relationships are used to determine the depth in the floodplain due to wave overtopping.

- Wave height (R) is determined from the still water level (SE) versus wave height and uncertainty relationships for each still water level.

- If the still water level alone exceeds the top of levee (SD), wave runup (RR) is equal to two-thirds of the wave height. If still water level (SE) alone is below the top of levee (SD), wave runup (RR) is equal to the full wave height (R).

$$RR = 2/3\ R \qquad (SE \geq SD)$$
$$RR = R \qquad (SE < SD)$$

- The exterior stage with wave (S_E) is computed by adding wave runup (RR) to still water level (SE).

$$S_E = SE + RR$$

- The total height above the levee (HW) is determined by subtracting the levee crest elevation (SD) from the exterior stage with wave (S_E). This height is set to zero if the exterior stage with wave (S_E) is equal to or below the top of levee (HW).

$$HW = S_E - SD \qquad (SE > SD)$$
$$HW = 0 \qquad (SE \leq SD)$$

- The wave shape factor (Z) is equal to the ratio of the portion of wave above the levee or floodwall to total wave height and is determined by dividing the total height (HW) by the wave runup (RR).

$$Z = HW/RR$$

- K, is a factor for determining the portion of the total water above the top of levee that is effective for overtopping and is dependant on the wave shape factor, Z, as defined by the entered relationship Z versus K.

- The total effective overtopping height (HO) above the top of levee is equal to K times the total height (HW) above the top of levee.

$$HO = K*HW$$

- The depth of water in the floodplain, referred to as interior stage (S_I) is the stage on the landward side or interior of the levee or floodwall and is dependant on HO as described by the entered relationship HO versus S_I.

- It should be noted that the relationship HO versus S_I should be defined for the full range of overtopping heights and interior stages. At some point, either by failure or sufficient overtopping, SI should equal the levee elevation (SD) plus the quantity (HO minus 2/3 R).

  $$S_I \Rightarrow SD + (HO - 2/3\ R)$$

  The exception would be if there was not sufficient volume available to fill the interior area to the same elevation as the exterior still water level.

Levees Subject to Geotechnical Failure - for existing levees or other levees subject to geotechnical failure, a relationship between water surface stage on the river or exterior side of the levee versus the probability of failure can be defined. When this is the case, a still water level versus wave height relationship may be defined to account for the effect of waves contributing to levee failure. Since the levee has a geotechnical failure relationship defined, overtopping parameters will not be available.

When a still water level versus wave height relationship is provided, the following two scenarios apply. The first scenario is if a given still water level fails the levee based on the geotechnical failure relationship, wave height is ignored and the still water level without wave is used to determine interior stage based on an exterior versus interior relationship. If the later relationship is not provided, the interior stage is assumed equal to the still water level. For the second scenario, if the still water level does not fail the levee based on the geotechnical failure relationship, sampled wave height is added to the still water level and compared to the top of levee stage. If still water level plus wave height is equal to or exceeds the top of levee, the levee is failed and the still water level without wave is used to determine interior stage based on an exterior versus interior relationship. If the later relationship is not provided, the interior stage is assumed equal to the still water level.

Testing consisted of re-entering the Hydrologic Engineering component data for both data sets. For the water surface profiles sets testing included importing the water surface profiles sets from HEC-RAS and HEC-2 generated files. Also, the testing included entering, modifying, and deleting the water surface profiles sets. The testing for exceedance probability functions included creating from a water surface profile, entering data for both types (analytical, graphical) of exceedance probability functions, and importing from an ASCII tab-delimited text file. Once the model has the data, when executed the model creates the exceedance probability function with uncertainty. Testing for stage-discharge functions included creating from a water surface profile, entering a stage-discharge function, and importing a stage-discharge function from an ASCII tab-delimited text file. Uncertainty for a stage-discharge function was tested by either entering the uncertainty values by hand, or have the model calculate the uncertainty based on data provided.

Since the two data sets that are provided do not cover all the available levee features, the only testing done was entering of the name, description, and top of levee stage. The testing of the relationships available for the levee was conducted using other data sets provided by USACE offices.

All of the items for the Hydrologic Engineering component have been tested and compared to results from previous test runs of previous model versions. The model passed the tests with the exception of the geotechnical failure and wave overtopping relationships defined for a levee. The two data sets provided for testing do not include these relationships as part of their data.

3.3.3 Technical Quality Assessment of Component Three – Economics

As discussed in Section 2.2.3, the Economics component of the model is where data and computations to produce stage-damage functions with uncertainty for flood risk management occurs for model analysis. This data is required for model analyses, and includes damage categories, structure occupancy types, structure modules, structure inventory, and stage-damage functions.

- Damage Categories

  Damage categories are used to consolidate large numbers of structures into specific categories of similar characteristics for analysis and reports. Typical damage categories include: residential, commercial, industrial, open space, and public facilities. At least one damage category needs to be entered with a maximum of twenty. It is recommended that the number of damage categories be kept to the minimum for computation considerations in the model.

- Structure Occupancy Types

  Structure occupancy types are defined by damage category, and the same structure occupancy type cannot be used for different damage categories. Structure occupancy types contain depth-damage functions where damage is defined in percent of value (structure, content, and other). Structures which have a direct depth-dollar damage function assigned to them have a structure occupancy type with a name that is generated by the model. Structure occupancy types are optional; however, if the model is going to compute stage-damage functions then structure occupancy types are required. Data required for structure occupancy types includes:

  Depth-Percent Damage Functions - a depth-percent damage function represents the damage caused to a structure, the contents of a structure, and "other" (other can be used to compute damage for any other item not accounted for in structure or content value, i.e., automobiles) for given depths of flooding at a structure. Depth-percent damage functions should always contains a zero damage depth, and negative depths are acceptable. The uncertainty associated with the depth-percent damage function is entered by ordinates based on the specified distribution.

Content to Structure Value Ratio - this value is used to estimate the total content value if the structure inventory does not include content value information. The ratio is entered as a whole number (i.e., enter 50 for a ratio of 50%). If the user is using generic depth-damage (EGM 04-01) relationships in the model, the user need to enter a value of 100 (100%).

Other to Structure Value Ratio – this value is used to estimate total value of the property represented by other if the structure inventory does not include other value information. The ratio is entered as a whole number (i.e., enter 50 for a ratio of 50%).

Uncertainty Parameters – distributions or uncertainties that are associated with estimating the depth-damage functions, structure values, content values ratios, other value ratios and first flood stage. These are used to develop the total aggregated stage-damage-uncertainty functions by damage categories for a damage reach. Parameters include first floor stage, structure value, content/structure value (left blank when suing generic depth-damage relationships), and other/structure value.

- Structure Modules

  Structure modules allow the model to vary one or more structure characteristics by plan and year or to include or exclude one or more structures from a plan/year. There is a default structure module (Base) and any new structure is automatically assigned to the default structure module. Structure modules must be defined prior to development of a structure inventory.

- Structure Inventory

  Structure inventories are a record of the attributes of unique or groups of structures relevant to flood risk management analysis. The inventory is used to compute an aggregated stage-damage function by damage category at the damage reach index location station. Structures are assigned to a specific damage category, structure occupancy type, stream, and structure module. The structure inventory can be entered directly or imported from an ASCII text file. For further information on developing structure inventories, refer to the following USACE reports by Institute for Water Resources:

  - "Natural Economic Development Procedure Manual - Urban Flood Damage", March 1988, 88-R-2
  - "Natural Economic Development Procedure Manual - Urban Flood Damage - Volume II: Primer on Surveying Flood Damage for Residential Structures and Contents", October 1991, 91-R-10
  - "Catalog of Residential Depth-Damage Functions", May 1992, 92-R-3
  - "Analysis of Non-Residential Content Value and Depth-Damage Data for Flood Damage Reduction Studies", April 1996, 96-R-12

Structure attributes include:

Name (required) – each structure must have a unique name – two structures cannot have the same name. If the same structure is used in more than one module, it must have a unique name for each module. The maximum length is sixteen (16) characters.

Stream Station (required) – stream station of where the structure is located on a stream and must be consistent between damage reach boundaries, damage reach index location, water surface profiles, and structure location. A valid value for a stream station is from 0 to 9,999,999.99.

Structure Value (required) – value of the structure (does not include the content value), a valid numeric value for the structure value ranges from 0 to 999,999,999.

Content Value (optional) – value of the contents (does not include the structure value) associated with a structure. A valid numeric value for the content value ranges from 0 to 999,999,999. If left blank, the model computes the content value from the content to structure value ratio that is defined in the occupancy type and the structure value. If a content value is entered, it will override the content value computed from the content to structure value ratio. If you enter zero, the content value will be zero. If the content damage is defined with a depth-direct dollar function, the content value is not used in the calculations.

Other Value (optional) – value of "other" property (does not include the structure value) such as outbuildings associated with a structure. A valid numeric value for the content value ranges from 0 to 999,999,999. If left blank, the model computes the "other" value from the other to structure value ratio that is defined in the occupancy type and the structure value. If an "other" value is entered, it will override the "other" value computed from the other to structure value ratio. If you enter zero, the content value will be zero. If the "other" damage is defined with a depth-direct dollar function, the "other" value is not used in the calculations.

Bank (required) – determines which stream bank (looking downstream) the structure is located on; the model allows the choice of either Left (default) or Right.

First Floor Stage (required) – the stages (elevations) associated with the first floor of the structure, the value must be between -300 to 30,000. Required if the ground stage and foundation height have not been entered.

Beginning Damage Depth (optional) – enter the beginning damage depth in feet (meters) relative to the first floor stage where damage begins. The beginning damage depth is normally used in the analysis of structures with basements where flood waters enter above basement floor. The beginning damage depth truncates the damage function at the specified depth. For example, if damage begins at one foot below the first floor stage, the beginning damage depth is set to -1.

Ground Stage (required) – the stage (elevation) of ground at the structure, this value must be between -300 to 30,000. Required if the first floor stage has not been entered.

Foundation Height (required) – the distance from the ground stage to the first floor stage. Required if a ground stage has been entered.

Depth-Direct Dollar Damage Functions (optional) – if the structure occupancy type for a structure is Direct, then a depth-direct dollar damage function will need to be entered. First, the model assumes the normal distribution for the first floor stage and a standard deviation for it even if it is zero (no uncertainty) must be entered. The direct-dollar functions are normally used to define unique damage potential such as some commercial, industrial, infrastructure, and public facilities. There are three types of depth-direct dollar damage functions – structure, content, and other.

Structure Coordinates (optional) – the UTM or other study adopted coordinates associated with the structure location; this is an optional item but is highly recommended.

- Stage-Damage Functions

USACE defines a stage-damage function as the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given river or damage reach. From the model you can enter stage-damage functions manually or the model will calculate stage-damage functions. For the model, a complete set of stage-damage functions for all categories, damage reaches, and streams must be entered to analyze a specific plan for an analysis year. The uncertainty is defined only by the normal probability density function. If there is no uncertainty, you must select the normal distribution and enter zeros for the standard deviations – don't leave the uncertainty field blank.

Computing Stage-Damage Functions – to compute stage-damage functions (aggregated damage) the model requires that several model items be defined. These include configuration items (plans, stream, damage reaches, analysis years), water surface profiles, damage categories, structure occupancy types, and structure attributes. It is also helpful to define the discharge-exceedance probability and stage-discharge functions. The structure attributes define the parameters necessary for computing stage-damage for each structure. The discharge-exceedance probability and stage-discharge functions are used to determine the span of stages at the index location for which aggregated damage is computed.

Once all of the above parameters are defined, then computing stage-damage functions for one or more combinations of plan and analysis year can happen. The computed functions are then used in the computation of expected annual damage. If any changes occur to any of the parameters such as a structure's first floor elevation, then the model will require a re-compute of stage-aggregated damage and then expected annual damage for all plan/analysis year combinations that are dependent upon that structure.

Below is a general overview of what happens in the model when a user requests a stage-damage compute for a plan/analysis year combination, for more details on the computation procedure for stage-damage function in the model see Appendix B:

1) For each damage reach, the model calculates the range of stages at the index location. The stages represent the range from very frequent to very infrequent events based on the input functions and the uncertainty about those functions. The model then calculates the interval between stage ordinates in favorable incremental units. The model determines the minimum and maximum values (the range) and then iterates through the range to find the appropriate incremental values. It uses 1, 2, or 5 times 10^n and the number of ordinates (a maximum of sixty ordinates can be selected) to find the appropriate incremental values.

2) For the selected plan/analysis year, the model filters the structures using the structure module assignments so that it will process only those structures which are assigned to the selected module(s). It also filters the structures based on the "Year in Service" parameter.

3) The model processes each of the filtered structures. It transforms the tabulation stages that were determined in Step 1 from the index location to the structure. The transformation uses either the water surface profiles or the SID reference flood.

4) The model checks each structure to see if it has invalid data and to see if the structure is "out of the floodplain". The model will immediately proceed to the next structure if either case exists.

5) The model determines the damage category, structure occupancy type, and damage reach, and then computes stage-damage at each of the tabulation stages for a structure. Damage is computed for the structure, contents, other, and total. The damage for each tabulation stage is then aggregated to the index location. During calculations, the stage-aggregated damage functions are stored in memory. After all of the filtered structures are processed, the stage-aggregated damage functions are stored.

Testing consisted of re-entering the Economics component data for both data sets (however, the Chester Creek data set does not include a structure inventory). For the damage categories testing included entering, modifying, deleting, and importing (ASCII tab-delimited file) the damage categories. The testing for structure occupancy types included entering, modifying, deleting, and importing (ASCII tab-delimited file) structure occupancy types. Associated with structure occupancy types are the depth-percent damage functions which were tested by entering, modifying, deleting, and importing (ASCII tab-delimited file) the functions. The uncertainty associated with a depth-percent damage function is entered (also can be imported). The structure inventory testing is only done in one of the provided data sets (Beargrass), for this data set the structure inventory is imported from an ASCII tab-delimited file. This includes the structure attributes, and the depth-direct dollar damage functions with uncertainty. Additional structure inventory testing, included entering, modifying, and deleting the structure attributes was also done.

Testing for stage-damage functions is done differently for each data set. For the Chester data set, since there is no structure inventory, the stage-damage functions are entered manually. So testing consisted of entering, modifying, deleting, and importing (ASCII tab-delimited file) of the stag-damage functions. Since, the Beargrass data set includes a structure inventory and all of the other required data pieces, the stage-damage functions are computed by the model. The testing included comparing the resulting stage-damage functions to prevision model version results, and hand calculations (done in Excel).

All of the items for the Economics component have been tested and compared to results from previous test runs of previous model versions; the model passed the all tests.

3.3.4 Technical Quality Assessment of Component Four – Evaluation

As discussed in Section 2.2.4, the Evaluation component of the model is where the computations for expected annual damage, equivalent annual damage, and project performance occur. Also, from this component the user can review the study status and view results.

- Expected Annual Damage (EAD) and Project Performance

  Monte Carlo simulation is used by the model to derive the expected annual damage corresponding to a particular plan/analysis year for a damage reach. The model needs to have several analysis variables to compute EAD and project performance. The model computes the following variables: 1) exceedance probability curves; 2) project reliability; 3) expected annual damage, 4) flood risk management benefits, and 5) probable flood stages conditional on the occurrence of a particular exceedance probability event. These variables are computed from various relationships that represent watershed runoff and economic factors important to estimating flood damage (e.g., discharge-exceedance probability, stage-discharge and stage-damage curves). The contributing relationships are characterized by both a best estimate and the uncertainty in this estimate. Details of the computational procedures are detailed in Appendix C.

- Equivalent Annual Damage

  Equivalent annual damage is computed by discounting future EAD values given the appropriate interest rate and time for discounting. EAD is calculated for the base year, however, it is common for conditions to change over time – damageable property in the floodplain may increase or decrease, urbanization upstream may cause increased runoff, or a channel may change. The necessary functions are entered for the future years, then the model interpolates stage, flow, and damage data from the base year to compute EAD for the future years. Now that EAD has been computed for each year throughout the period of analysis, the remaining step is to discount all of these values back to time zero (beginning of base year) and amortize the present value over the period of analysis. The model discounts each individual year and amortizes the sum. This computation is applied to not only the best estimate of EAD but to the distribution of possible EAD values obtained as part of the Monte Carlo simulation. This results in a distribution of equivalent annual damage.

Inundation reduction benefits are computed as the difference between with-and without-project equivalent annual damage. This differencing is performed between the distribution of equivalent annual damage values obtained for both with-and without-project condition resulting in a distribution of equivalent annual damage.

The differencing of uncertainty distributions in this manner recognizes that irrespective of the plan, the future exceedance probability of events causing floods will be the same for all plans. Consequently, differencing these distributions results in the same answer as would be obtained by obtaining the distribution of net benefits by performing Monte Carlo simulation of damage differences.

Testing consisted of re-computing the Evaluation component computations for both data sets. For the Expected Annual Damage (EAD) and Project Performance, computations were re-run for all plans and analysis years (this is eight separate runs). Results then were compared to runs from previous versions of the model. Also, results are compared to hand calculations to make sure the model is computing the Monte Carlo simulations correctly.

Testing for the Equivalent Annual Damage computations were re-run for all plans (this is four separate runs), results then were compared to runs from previous versions of the model. Also, results are compared to hand calculations.

3.4 System Quality Assessment

The system quality of HEC-FDA has generally been assessed via the routine installation and operation of the model, rather than according to a set of discrete tests or component assessments identified in advance, although some exercises were specifically undertaken to investigate certain aspects of the model associated with system quality.

3.4.1 Installation and Operation

HEC-FDA is a Windows-based, menu driven interface application. It is a data-driven model, with the data elements stored in a relational database, while the process descriptions are embodied in the software itself (computational engine). The user interface is responsible for data editing and reporting, while the computational engines read the databases, perform the necessary simulations, writes output files and writes out information back in the appropriate databases, for additional reporting and visualization. The stage-damage function computational engine is written in C++; databases are stored using an Xbase library (Codebase) which is C++; the user interface is written in C++; the EAD and equivalent annual damage computational engines are written in FORTRAN. The output files obtained from the user interface are written to databases, while some results from the stage-damage computational engine are written to ASCII flat files. However, an assessment for suitability of the basic programming language used to compile the model and examination of the source code were not included in the scope of this particular review.

The version of the model made available for the review was downloaded with the Beargrass Creek and Chester Creek data sets from http://www.hec.usace.army.mil in November 2008. The data sets consisted of the input and output databases. The version number of the model was 1.2.4.

For the purposes of the review and certification process, the most recently available version of HEC-FDA was installed on two host computers by the HEC development team. The HEC development team found that, with the help of an IT Administrator, installation of the model was a fairly quick and straightforward process on all of the host computers. The processes of installation and the specification of target directories on the host computers for the downloading of the components were identical for each computer, and the model was fully executable and operable on both computers.

The installation and operation of HEC-FDA requires no prior installation of additional software beyond that which is commonly found in the planning community, assuming that a recent version of the Windows operation system and Microsoft Excel are industry-standard tools. The relational database embedded within the model is in Xbase format which allows the user to view the data outside of the model using additional software (i.e., Visual dBase, dBase Plus).

When successfully executed through to the generation and output of results, the HEC development team generally did not experience any problems with regard to the speed of execution when operating the model on any of the host computers.

3.4.2 Model Stability

Generally speaking the model is stable, however, there are times when the model can crash or terminate prior to completion of data entry. Usually the model is quite stable during computation of the stage-damage functions, EAD, and equivalent annual damage. For further information on reviewing several text files that the model writes, and log files and a table of known error messages, see Chapter 16 of the Draft HEC-FDA User's Manual (November 2008).

3.4.3 Model Interoperability

The assessment of system quality also considered the ability of the model to import data to and from other software analysis tools. The HEC development team expects that most practical application of the model will make use of the model's facility to import the key project data using Excel® spreadsheets and then creating an ASCII tab-delimited text file that the model can import. The model also has the capability to export data from the database files that contain key data.

3.5 Usability Assessment

The overall assessment of model usability has been formulated through a comprehensive review of the supporting documentation and through the general use and operation of the model. The HEC-FDA development team generally divided observations and concerns regarding the usability of model into the following subject areas: Supporting Documentation, Training, Software Support/Maintenance, and User Interfaces.

3.5.1 Supporting Documentation

The usability of the model depends to a great extent on the clarity and efficiency with which the supporting documentation informs the user of the data required and the process that must be followed in order to obtain the desired outputs. The main supporting document evaluated by the HEC-FDA development team for the usability assessment was the document "HEC-FDA, Flood Damage Reduction Analysis, User's Manual, Draft, Version 1.2.4, November 2008". This manual is an update of the manual that was released in January 1998. The HEC-FDA development team was also provided with a package of internal documents and records pertaining to the history and development of HEC-FDA. Also, various papers and presentations have been written about using the model. Several of these have been published as Research Documents, Technical Papers, Training Documents, and Seminar Proceedings which are available at the following website www.hec.usace.army.mil.

Several USACE offices have written papers and documents on using the model in flood risk management studies. The HEC-FDA development team recommends for additional documentation that an applications guide on using the model should be written and published by HEC.

3.5.2 Training

Also, USACE provides training under the PROSPECT program on the use of the model, and the concepts of risk analysis procedures for formulating and evaluating flood risk management measures. This training increases the user's knowledge, proficiency, ability, and skill in the use of the model. Since the initial release of the model, this training has been provided on average yearly through the PROSPECT program.

3.5.3 Software Support/Maintenance

Since the model was released in 1998, the HEC has provided support to USACE and offices outside of the federal realm. Maintenance and updates have been provided ever since to USACE offices.

3.5.4 User Interfaces

The term "User Interfaces" has been taken to cover the on-screen appearance and structure of the model and the output it generates. In general the HEC-FDA development team considered this aspect of the model to be well-designed, logically structured, and visually very well presented.

- Interpretation and Post-Processing of Results

  The clarity and accessibility of generated results is a key factor in assessing the usability of the model. The current version of the model generates results in two formats: a suite of summary tables and graphs accessible through the model's user interface, and also a set of more detailed output from the stage-damage computations of the model. These sets of files are ASCII tab-delimited files, which are easily viewable in other software programs.

  The summary tables and graphs are accessible and provide the information that is required for risk analysis in USACE guidance. However, the reports and graphs could be labeled a little better, and should probably meet the formats of the report requirements stated in USACE guidance. The detailed output from the stage-damage calculations in the model supply the user with an impressive amount of results data, but the supporting documentation does not currently provide the user with comprehensive guidance as to the control of these outputs, their contents, and their interpretation. Currently in the model there is no direct way from the model's user interface to obtain key stage-damage data directly. The graphical displays generated by the model are generally well done the HEC-FDA development team thought.

- Help

  The help system provided in the model is based on the HEC-FDA User's Manual and provides general user assistance. At the dialog box level, the model also provides context-sensitive help for the user. The over all help system of the model is robust and provides excellent user assistance.

SECTION 4

Conclusions and Recommendations

4.1 General Review Summary

The following table presents a general summary of criteria used to review the model. The format mirrors the outline of technical documentation for use in model certification as suggested in the PMIP Protocols. This table is intended to provide a general overview of the more detailed discussion of the findings and observations presented in Sections 3.3 through 3.5.

General Certification Criteria	Assessment
Technical Quality	
Theory	The overall theoretical approach and methodologies on which HEC-FDA is based are valid.
Description of the system being represented by the model	The model provides an accurate and realistic representation of the physical processes affecting flood risk management and the economic consequences.
Analytical requirements and assumptions	The model fulfills technical requirements that have been based on formal documentation of analytical requirements. Not all model assumptions are explicitly documented.
Conformance with USACE policies and procedures	The model is in overall compliance with current USACE policy.
Formulas used in the model are identified and the computations are appropriate and done correctly.	Most of the formulas used in the model are generally identified in the supporting documentation.
System Quality	
Description of and rationale for selection of supporting software tool/programming language and hardware platform.	The software and hardware requirements are appropriate.
Proof that the programming was done correctly.	Examination of the source code was not included in the scope for the review of HEC-FDA. However, the model has been in practice for many years and its procedures have been reviewed by NRC and others, and have passed their tests.
Description of process used to test and validate model.	Developers used Chester Creek, PA as the principal test bed study. The review team conducted individual tests on selected parameters and applications, verified by comparison with manual calculations or output from external independently validated software where possible.

General Certification Criteria	Assessment
Ability to import data into other software analysis tools (interoperability issue).	General availability of Excel is assumed for importing and exporting of original study data.
Usability	
Availability of input data necessary to support the model.	Significant time and specialist effort is required to generate and collate most of the key input datasets, irrespective of the size of the project.
Formatting of output in an understandable manner.	In general, the format of the reports is clear and generally matches the format stated in USACE guidance. Some of the reports need to be adjusted for better user friendliness and more in-line with the USACE guidance.
Usefulness of results to support project analysis.	The content and level of detail of results is invaluable to the engineer responsible for the study.
Ability to export results into documentation.	Results can be easily exported into other documentation, subject to formatting and post-processing.
Training availability	There is adequate training within USACE for the model.
Users documentation availability and whether it is user friendly and complete	Current supporting documentation (principally the User's Manual) is considered complete, but probably could be refined so that some of the areas are more intuitive.
Technical support availability	For USACE users, the model has technical support available.
Software/hardware platform availability to all or most users.	Hardware and software requirements for installation and operation of the model are considered to be industry standard.
Accessibility of the model	Currently available for download from the HEC website.
Transparency of model and how it allows for easy verification of calculations and outputs.	The model is considered not fully transparent in some areas, and detailed guidance as to the understanding and interpretation of the output is required for verification of the results.

4.2 Certification Recommendations

HEC-FDA is a highly complex model drawing together theory and data from numerous specialist fields and disciplines into a powerful analytical tool that has widespread application in the planning community. It features an impressive degree of detail and is capable of a very high level of computational precision, providing planners with the techniques and analysis required to include appropriate flood risk management decisions.

One of the primary aims of this review and documentation was to generate recommendations regarding certification in accordance with the PMIP Protocols. This review needed to determine the extent to which the model satisfies analytical and policy requirements in USACE for risk analysis. The HEC-FDA development team recommends that the reviewed version (1.2.4) of HEC-FDA be certified as a USACE Corporate model for nationwide implementation.

APPENDIX A

References

A.1 Required Publications

These documents define policy and basic methods directly related to hydrologic engineering for flood risk management planning by USACE. All are promulgated by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC.

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EC 1110-2-554
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EC 1110-2-6067
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EGM 01-03
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Engineering and Design - Hydrologic Frequency Analysis, Mar 1993. Department of the Army, USACE, Washington, DC 20314-1000.

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ETL 1110-2-532
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ETL 1110-2-537
Engineering and Design - Uncertainty Estimates for Nonanalytic Frequency Curves, October 1997. Department of the Army, USACE, Washington, DC 20314-1000.

ETL 1110-2-546

Engineering and Design – Provisions to Set Final Levee Grade for Projects Formulated Using Risk-Based Analysis, September 1995. Department of the Army, USACE, Washington, DC 20314-1000.

ETL 1110-2-547
Engineering and Design - Introduction to Probability and Reliability Methods for Use in Geotechnical Engineering, September 1995, Department of the Army, USACE, Washington, DC 20314-1000.

ETL 1110-2-549
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A.2 Other Publications

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APPENDIX B

Procedures for Computing Stage-Damage Functions

B.1 Introduction

This appendix describes and illustrates the calculation procedures used by HEC-FDA to compute stage-aggregated damage at the index location. The calculations require the user to already have entered supporting data. Calculations are performed by a plan/analysis year combination, if more than one plan/analysis year combination has been selected; the model processes each one independently and loops through all selected combinations.

For discussion purposes in this appendix, an imaginary study is created on Silver Creek. The study area is divided into five reaches as shown in Table B.1. There is an overlap of damage reaches SC 2L and SC 2La. That is, they represent the same stream (Silver Creek), station range (20.002 through 29.998), and bank (Left). Discussions later on will illustrate situations where this can be used to a user's advantage. For now, the discussion will center on computing stage-damage for several structures (located on the right bank) within damage reach SC 2R. The index point is located at station 25.000 (river mile 25.000). The stage-damage function for each structure is aggregated to the index location.

Table B.1
List of Damage Reaches for Silver Creek

Reach Name	Beginning Station	Ending Station	Bank	Index Location Station	Description
SC1	20.000	20.001	Left	20.000	Bottom of study area. RM 20.000
SC 2L	20.002	29.998	Left	25.000	Reach SC 2L, Sliver Crk. Left Bank
SC 2La	20.002	29.998	Left	25.000	Reach SC 2La, Sliver Crk. Parallels Reach SC 2L. Protected by Levee.
SC 2R	20.000	30.000	Right	25.000	Reach SC 2R, Silver Crk. Right bank.
SC 3	29.999	30.000	Left	30.000	Top of study area. RM 30.0

B.2 Setting Up the Stage-Damage Calculation

Initially, the model builds storage locations in memory for the stage-aggregated damage functions. The model determines the total number of damage reaches for all streams and the number of damage categories. For each reach, the model determines the range of stages required to cover the entire range of events from frequent to infrequent. The model attempts to determine this range first by retrieving the discharge-exceedance probability and stage-discharge functions (or stage-probability function). If these are not available, the model retrieves the water surface profile information. If this is not available, the model cannot determine the required range of stages at the index location and the calculation procedures will not proceed.

To initialize and scale the stage-aggregated damage matrix, the model must retrieve the discharge-exceedance probability and stage-discharge functions for damage reach SC 2R. Table B.2 lists Log Pearson Type III Statistics for the hypothetical damage reach SC 2R. The number of years is the

Table B.2
Log Pearson Type III Statistics for Damage Reach SC 2R

Mean	3.000
Standard Deviation	0.200
Skew	0.400
Number of Years	50

equivalent length of record and is a measure of the uncertainty in the statistics. The model computes discharge-exceedance probability curve ordinates as shown in Table B.3. Although these are generated from Log Pearson Type III Statistics, they could have been generated from either

Table B.3
Probability Ordinates, Damage Reach SC 2R

Probability	Discharge	95%	5%
0.9990	312	240	378
0.9900	393	315	464
0.9500	496	413	571
0.9000	567	483	646
0.8000	675	587	758
0.7000	770	679	859
0.5000	970	869	1,080
0.3000	1,243	1,115	1,403
0.2000	1,456	1,297	1,670
0.1000	1,834	1,606	2,168
0.0400	2,377	2,028	2,927
0.0200	2,833	2,369	3,595
0.0100	3,335	2,734	4,355
0.0040	4,081	3,263	5,530
0.0020	4,711	3,698	6,555
0.0010	5,410	4,170	7,725
0.0001	8,306	6,046	12,868

synthetic statistics or from graphical coordinates. For scaling, the model uses the extreme ordinates of flow corresponding to probabilities 0.999 and .0001 which represent return intervals of about one and 1,000 years. For risk analysis, discharges corresponding to the 95% (240 cfs) and 5% (12,868 cfs) confidence limit curves are used for computing the required scaling for stage-damage computations. Figure B.1 depicts the discharge-exceedance probability curve with confidence limits.

Once the discharge-exceedance probability curve is retrieved and the extreme discharge values are determined, the stage-discharge function is retrieved and used to determine the corresponding

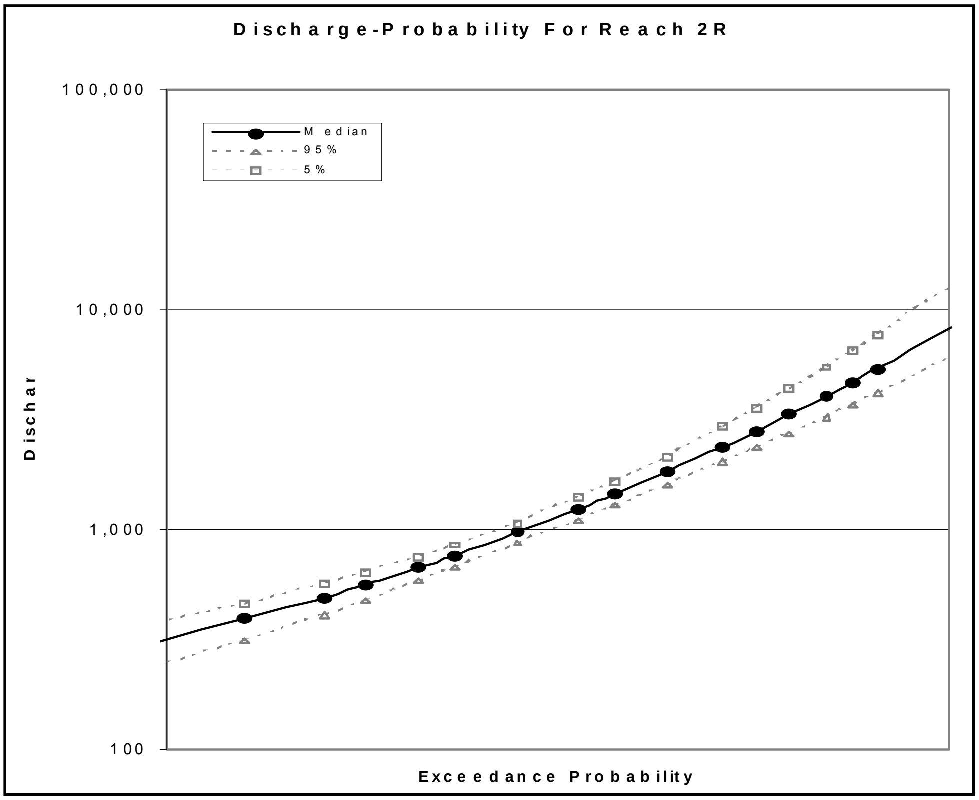


Figure B.1 Discharge-Exceedance Probability Curve for Damage Reach SC 2R

stages. Figure B.2 graphs the stage-discharge rating curve for damage reach SC 2R. Table B.4 lists the stage-discharge ordinates for damage reach SC 2R. They were computed from water

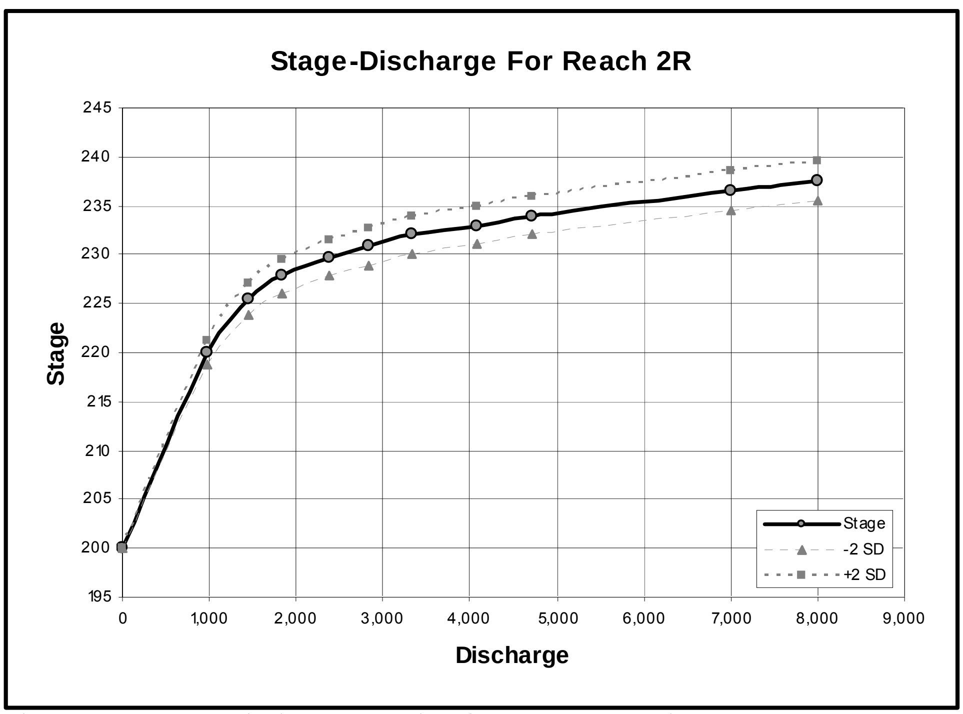


Figure B.2 Stage-Discharge Function for Damage Reach SC 2R

Table B.4
Stage-Discharge Function for Damage Reach SC 2R

Discharge	Stage	-2 SD	+2 SD
0	200.00	200.00	200.00
970	220.00	218.75	221.25
1,456	225.50	223.91	227.09
1,834	227.80	226.06	229.54
2,377	229.70	227.84	231.56
2,833	230.80	228.88	232.73
3,335	232.00	230.00	234.00
4,081	233.00	231.00	235.00
4,711	234.00	232.00	236.00
7,000	236.50	234.50	238.50
8,000	237.50	235.50	239.50

surface profiles. Since the model will not extrapolate the rating curve, additional points beyond the standard eight profiles were calculated for very high discharges of 7,000 and 8,000 cfs. Stages are interpolated from this table using the extreme discharges of the probability function with the extreme stages from the rating curve. The discharges of 240 cfs and 12,868 cfs correspond to stages of 204.64 and 239.5. Note that the maximum stage is truncated at the highest value on the rating curve for two standard deviations. The model then calculates a range of stages that meet the following criteria:

- encompass the range of stages from 204.64 through 239.5 feet.
- have an interval that is either one, two, or five times ten raised to some power. For example, 2.0×10^{-1} creates an array of stages 0.2 feet apart.
- have at least twenty but not more than thirty ordinates (this is an input option that you can change to allow a maximum of sixty ordinates). For this example, both the minimum and maximum number of ordinates was set to thirty.

For example, the stages in the stage-aggregated damage matrix for damage reach SC 2R are computed as:

- thirty ordinates
- minimum stage is 204.0 feet
- maximum stage is 262.0 feet
- interval between stages is 2.0 feet

The model now allocates memory for the array of stages and additional space for the corresponding aggregated damage and uncertainty (which will be computed) for all damage categories and stores the stages in this block of memory. All damage reaches are processed in the same manner as damage reach SC 2R.

If the discharge-exceedance probability and/or stage-discharge functions are not stored in the database, the model determines the range of stages from the water surface profile information. However, the default profiles include only a range of probability starting at 0.50. The resulting stage range could easily start too high. For example, if the functions were not available for damage reach SC 2R, the use of profile information would result in an array of thirty stages ranging from 219.0 to 248.0 feet at an interval of 1.0 feet. This may cause truncation of damage for infrequent events.

B.3 Computing Stage-Damage at Individual Structures Without Uncertainty

Once memory is allocated for the stage-aggregated damage matrices and the range of stages is determined for all reaches and all damage categories, the model begins processing all structures that meet the plan/analysis year filter. The plan year filter selects all structures which belong to the same structure modules that have been assigned. By default, the base structure module is always included although it may be an empty structure module (no structures assigned to this structure module). By default, each structure is assigned to the base structure module but it may be overridden. This section describes the processes and calculations at several structures which meet the plan/analysis year filter.

B.3.1 Calculating the Assumed Water Surface Profile Elevations at the Structures

Stage-damage at one structure is computed by calculating the water surface profile stages at the structure, determining the depth of flooding, and calculating the damage using values (structure, content, other) and depth-damage functions. The assumed stages at the structure correspond to the stages in the stage-aggregated damage function at the index location after adjusting for the slope of the water surface profile(s) between the index location and the structure. If the calculations use the water surface profiles (the eight standard profiles), the stages are adjusted using all eight profiles. If the SID reference flood water surface profile is used, then only one profile is used to adjust the stages.

Description of Sample Data – Profiles and Structures

Table B.5 lists the water surface profile stages at three cross-sections (station 20.0, 25.0, and 30.0). Stages are tabulated under their associated probability. For example, at station 25.000 (river mile 25.000), the stage for the 0.01 probability event (100 year return interval) is 232.0 feet.

Table B.5
Stage Water Surface Stage Profiles, Without Condition

Station	Invert	0.500	0.200	0.100	0.040	0.020	0.010	0.004	0.002
20.000	150.0	158.0	161.2	163.1	164.7	165.9	166.7	167.1	167.3
25.000	200.0	220.0	225.5	227.8	229.7	230.8	232.0	233.0	234.0
30.000	209.0	236.0	246.0	252.0	257.6	261.6	264.6	266.6	267.6

Figure B.3 graphically displays these same values. At the lower end of the study area (station 20.000), the profiles are relatively close compared to the upper end. The index location for reach SC 2R is at station 25.000. To illustrate the aggregation process, three identical structures are

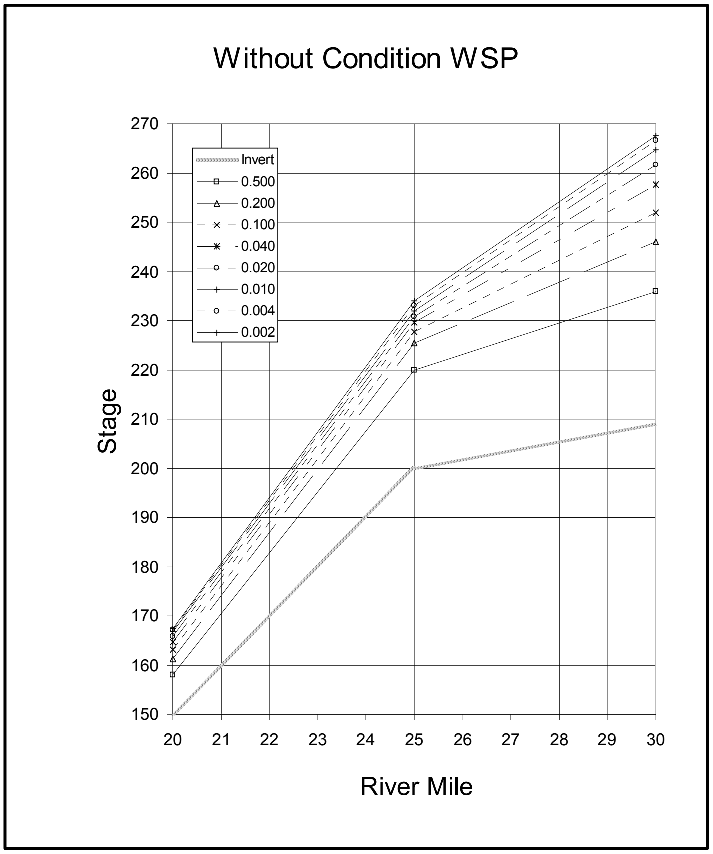


Figure B.3 Water Surface Profiles, Without Condition

used to calculate damage - one at the index location (station 25.000), and one at each of the extreme limits of the study (station 20.000 and 30.000). Table A.6 lists the appropriate characteristics for each structure. The first floor stage of each structure is located at the same stage as the 10% chance event. This will help illustrate several points about the calculations including using the eight water surface profiles as opposed to just the SID reference flood profile, having nonparallel profiles, and the location of each structure as defined by the structure station. Each structure is valued at $100,000. The contents are valued at $50,000 and it is calculated using

Table B.6
Structure Characteristics for Aggregation

Characteristic	Structure		
Name	**R0001**	**R002**	**R003**
Station	20.000	25.000	30.00
Structure Value	100	100	100
Content Value			
Other Value			
Bank	R	R	R
Damage Category	SF Residential	SF Residential	SF Residential
Occupancy Type	SF OS NB	SF OS NB	SF OS NB
Stream	Silver Creek	Silver Creek	Silver Creek
Module	Base	Base	Base
First Floor Stage	163.1	227.8	252.0

the global "ratio of content-to-structure value" which is defined within occupancy type SF OS NB which also contains the depth-percent damage functions. All three structures are located on the right bank.

Calculating Sample Aggregation Stages

To determine the assumed (or aggregated) water surface stages at each structure, the water surface profiles are used to generate a family of profiles which correspond to the aggregation (tabulation) stages at the index location. For structure R002 which is located at the index location, the assumed water surface stages correspond exactly to the aggregation stages. For structures R001 and R003, the assumed stages at the structure must be calculated. For aggregation stages above the rarest event (.002) or below the most frequent event (.500), aggregation profiles are parallel to the adjacent probability profile (.002 and .500 probability events respectively). Aggregation profiles between these two extremes are calculated using simple ratios of the computed water surface profiles. Table B.7 lists the aggregation profile stages at river mile 20.000, 25.000, and 30.000 which correspond to the three hypothetical structures. The lowest profile (.500 probability) is at stage 220.0 at the index location. All aggregation profiles below this minimum are parallel. For example, the .500 probability profile drops 62.0 feet from 220.0 at the index location to 158.0 feet at station 20.0. The same is true of the lowest aggregation profile which drops from 204.0 feet at the index location to 142.0 feet at station 20.00. Aggregation profiles above the maximum water surface profile are parallel to the 0.002 probability profile which reaches 234.0 feet at the index location. Aggregation profiles between 220.0 and 234.0 feet are computed using ratios. For example, the aggregation profile which has a stage of 230.0 feet at the index location has stages of 165.03 and 258.69 at river mile 20.000 and 30.000 respectively. Figures B.4 and B.5 depict selected water surface profiles and aggregation profiles for river miles 20.000 through 30.000 and 25.000 through 30.000 respectively. Note that the aggregation profile for a stage of 210.0 at the index location actually crosses below the invert at river mile 20.000 because the water surface slope is much greater than the invert.

Table B.7
Aggregation Profiles at Selected Locations

	River Mile (station)		
	20	**25**	**30**
1	142.00	204.00	220.00
2	144.00	206.00	222.00
3	146.00	208.00	224.00
4	148.00	210.00	226.00
5	150.00	212.00	228.00
6	152.00	214.00	230.00
7	154.00	216.00	232.00
8	156.00	218.00	234.00
9	158.00	220.00	236.00
10	159.16	222.00	239.64
11	160.33	224.00	243.27
12	161.61	226.00	247.30
13	163.27	228.00	252.59
14	165.03	230.00	258.69
15	166.70	232.00	264.60
16	167.30	234.00	267.60
16	169.30	236.00	269.60
18	171.30	238.00	271.60
19	173.30	240.00	273.60
20	175.30	242.00	275.60
21	177.30	244.00	277.60
22	179.30	246.00	279.60
23	181.30	248.00	281.60
24	183.30	250.00	283.60
25	185.30	252.00	285.60
26	187.30	254.00	287.60
27	189.30	256.00	289.60
28	191.30	258.00	291.60
29	193.30	260.00	293.60
30	195.30	262.00	295.60

Aggregation Methodologies

There are two methods for aggregating stage-damage to the index location. The difference between the two is the source of water surface profiles. The sources are:

- The set of eight water surface profiles.
- The SID reference flood water surface profile.

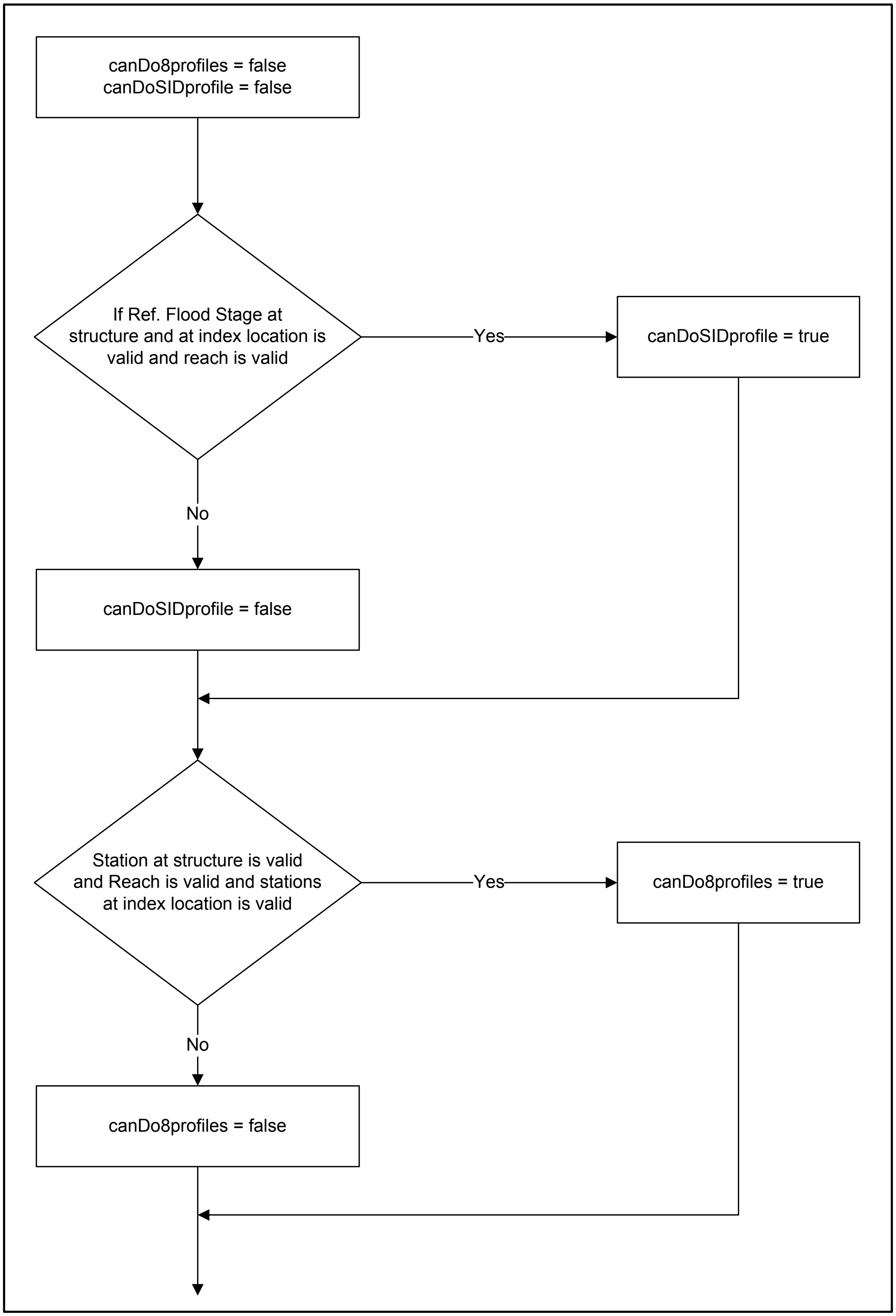


Figure B.4 Logic for Testing Data Validity of Aggregation Methodologies

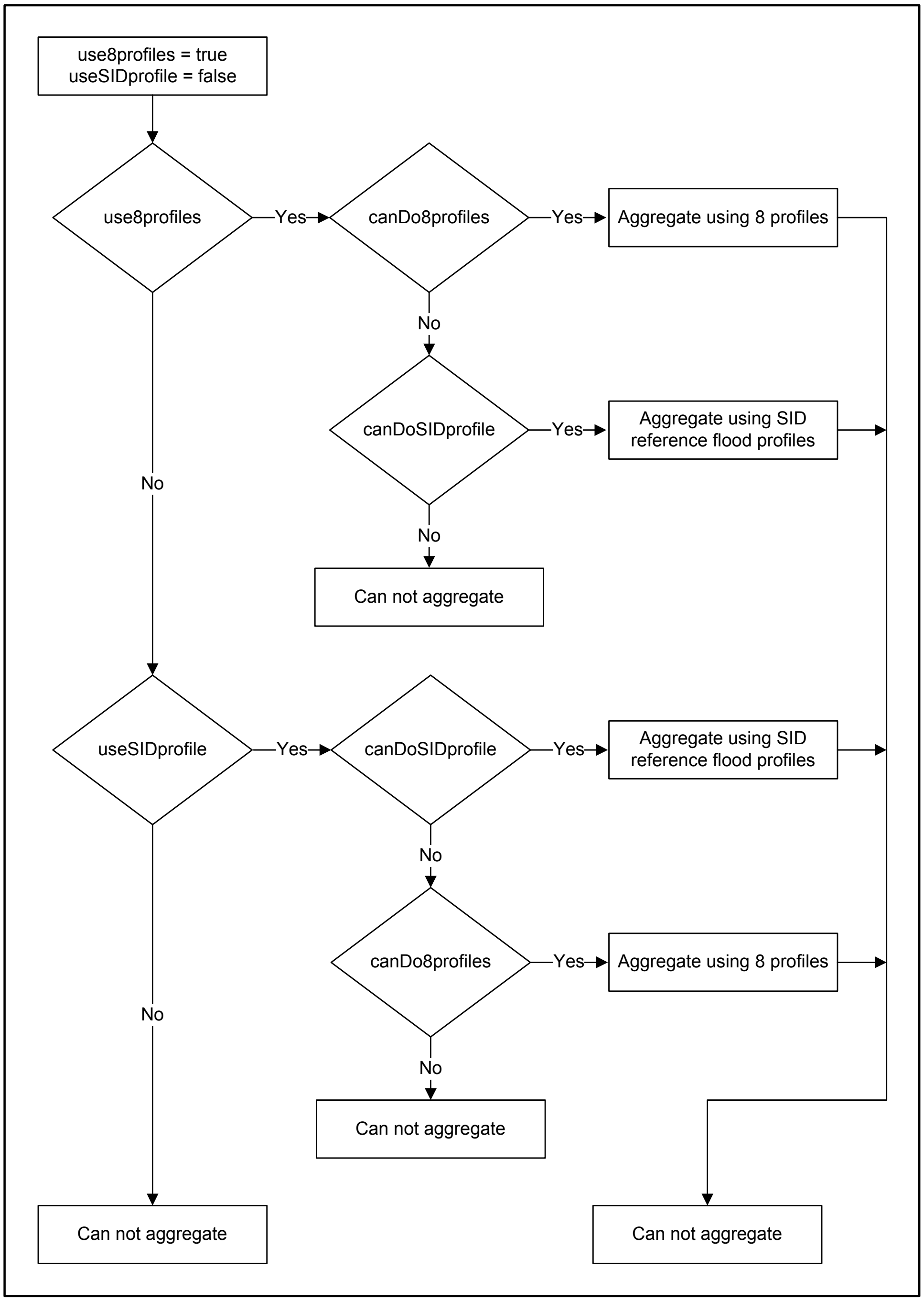


Figure B.5 Logic for Determining Aggregation Methodologies

The use of the eight water surface profiles facilitates accurate calculations when water surface profiles are not parallel. The use of the SID reference flood profile facilitates calculations using the old HEC-SID methodologies or calculations which require special circumstances. These circumstances might include:

- No profiles are available and water surface profiles are assumed to be flat.
- The profiles in the over-bank area are significantly different than those in the channel and a separate "stream" is not used.

Results using the single SID reference flood profile are identical to using eight parallel water surface profiles.

Data Requirements for Aggregation

The following data are required for aggregation using the eight water surface profiles:

- The structure must be assigned a valid stream, station, and bank.
- A set of water surface profiles must be entered for the desired plan, analysis year, and stream. The cross-section stationing must include the structure station.
- A damage reach must be defined which embodies location criteria of stream, bank, and beginning/ending stations that encapsulate those specified for the structure.

The following data are required for aggregation using the SID reference flood water surface profile:

- SID reference flood water surface stage at the structure.
- SID reference flood water surface stage at the index location.

The SID reference flood stage may be entered in the GUI for the structure but not for the index location - it must be defined either through import or using commercial database software.

Selecting the Aggregation Methodology

The user selects the desired methodology to use for aggregation. To use the SID reference flood for aggregation purposes, the analysis must have the parameter Use SID Ref Flood selected for each plan/analysis year combination. If the parameter is not selected, then the eight water surface profiles are used. However, if the structure does not satisfy the data requirements for the desired methodology, the model attempts to use the alternate methodology if data is available. This allows a mixture of methodologies within a selected plan/analysis year. Figure B.4 depicts the logic that the model uses for determining the possible aggregation methodologies for the selected structure. When aggregating damage at a structure, the model determines the possible methodologies using the logic of Figure B.4 and then uses the logic of Figure B.5 for calculation purposes.

B.3.2 Computing Damage for One Aggregation Stage Without Uncertainty

Overview

Damage is calculated at the structure for each of the stages listed in Table B.7. In this example, the three structures are located at stations 20.000, 25.000, and 30.000 and the corresponding stages are tabulated. If a structure is located between any of these stations, the model will make the appropriate interpolations. The model computation algorithm assumes the highest stage first (262.00 at the index location) and descends to the lowest (204.00 at the index location). If calculated damage is zero for three consecutive stages, the model assumes the zero-damage point has been reached and terminates calculations for the current structure. The calculation procedures accept as input the basic structure information as well as the associated data such as damage category and structure occupancy type. The following data is used as input to the calculations:

Structure Information
- Stream
- Station
- Bank
- Optional SID data (SID reach name, reference flood stage)
- First Floor Stage (or ground stage and foundation height)
- Beginning damage depth (optional)
- Damage Category Name
- Structure Occupancy Type Name
- Depth-Direct Dollar Damage Functions for this structure (optional)
- Module
- Number of Structures
- Values (structure, content, other)
- Year in Service

Related Information from the following:
- Damage Category
    - Price Index (optional)

- Structure Occupancy Type
    - Depth-Damage Functions (structure and/or content and/or other) with optional uncertainty parameters.
    - Content to Structure Value Ratio (percent)
    - Other to Structure Value Ratio (percent)
    - Uncertainty Parameters
        - First Floor Stage
        - Structure Value
        - Content to Structure Value Ratio
        - Other to Structure Value Ratio

- Streams
    - Stream Name

- Damage Reaches
    - Stream
    - Bank (left, right, or both)
    - Stations - Beginning and Ending
    - Reach Name (Used with SID reach names)

Other data/information may be entered for the structure, but it is not currently used in the computations. Some of the above data overlaps. For example, the user may define the first floor stage directly, or you may define it using the ground stage and the foundation height.

The example data set includes the occupancy type Single Family Residential, without basement. Table B.8 lists the depth-percent damage functions for the Single Family, Residential, without basement (SF OS NB) structure occupancy type. The functions are specified for structure and

Table B.8
Single Family, Residential, Without Basement Structure Occupancy Type Damage Function

Depth (feet)	Structure (percent damage)	Contents (percent damage)
-1	0	0
0	5	2
1	7	5
2	10	15
5	25	50
10	50	80
15	70	90
20	80	95

content but there is no damage to other. Figure B.6 depicts these same functions. Figure B.7 depicts the model stage-damage calculation procedure. The aggregation profiles (shown in

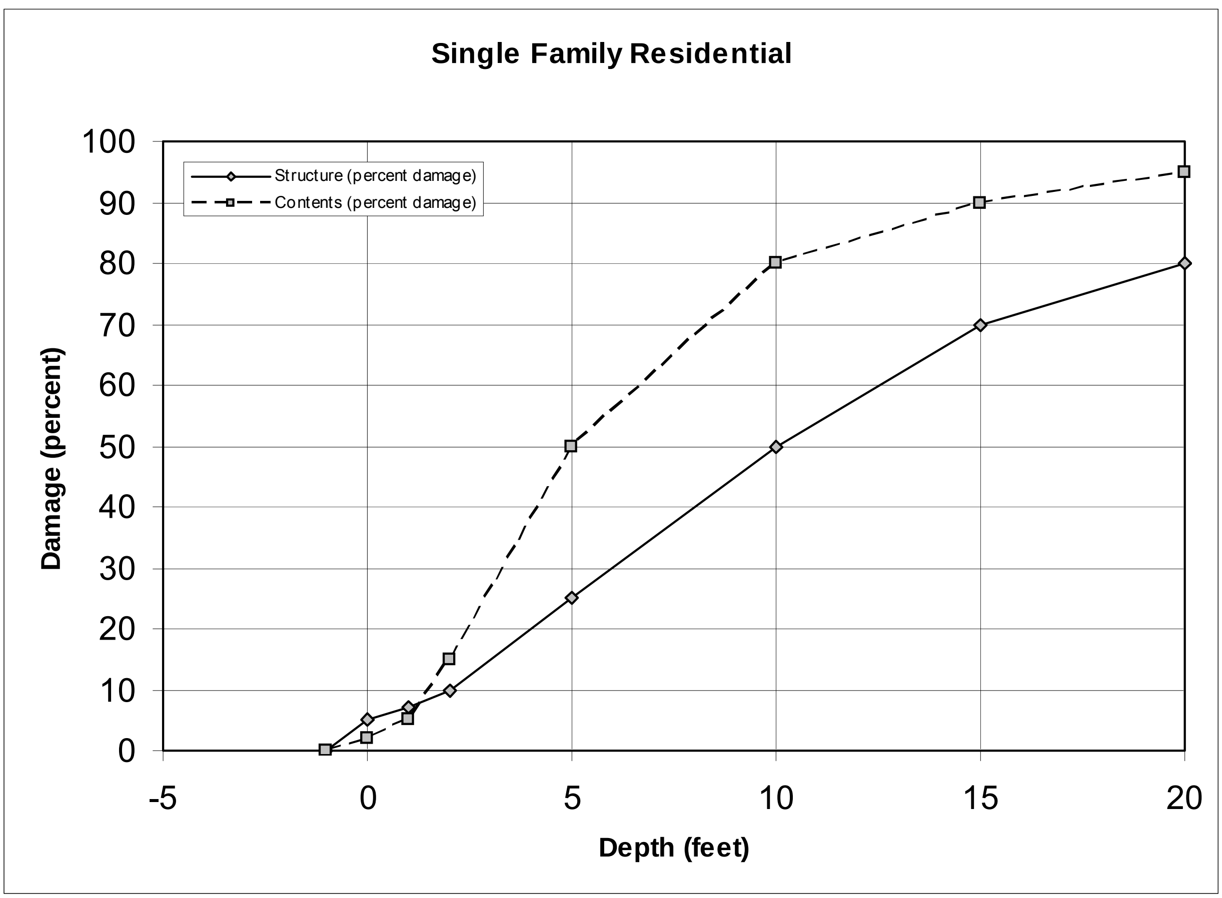


Figure B.6 Single Family, Residential, Without Basement Structure Occupancy Type Data Function

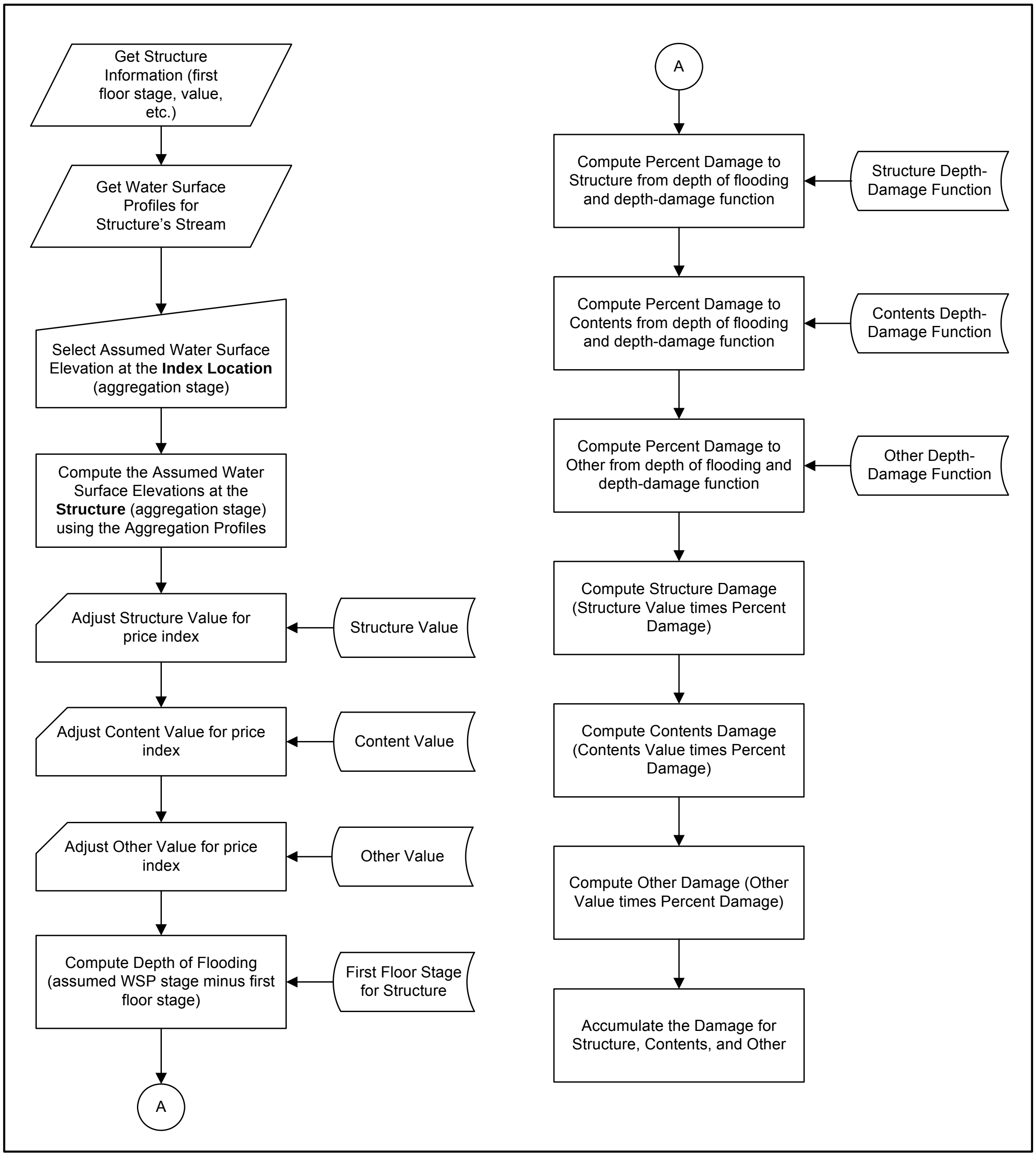


Figure B.7 Calculating Stage-Damage Without Uncertainty, One Ordinate

Figure B.8, Figure B.9 and Table B.7 are used to compute the "Assumed Water Surface Elevation at the Structure" (or Aggregation Stage) which is used to compute the depth of flooding. Figure B.7 depicts the process for one ordinate at one structure without using risk analysis procedures.

Procedure for Calculating Stage-Damage Without Uncertainty

The following section describes the stage-damage calculations depicted in Figure B.7 in more detail. Table B.9 lists and Figure B.10 graphs results for structure R003. The model writes this

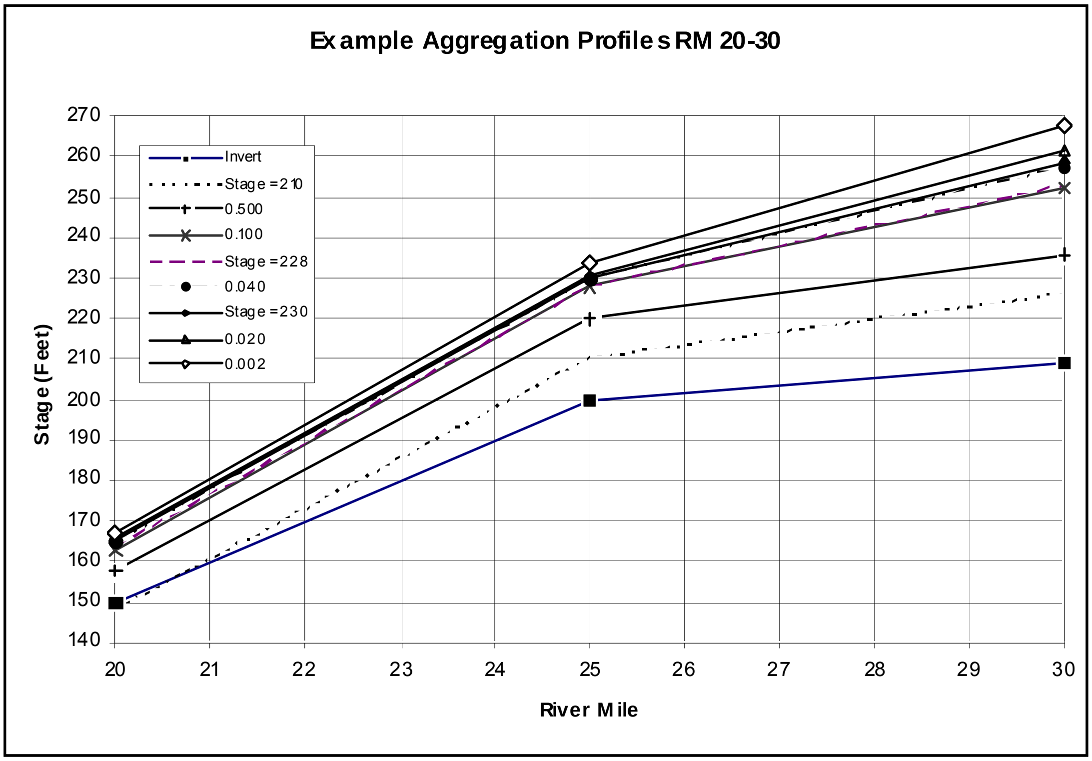


Figure B.8 Selected Aggregation and Water Surface Profiles RM 20.00 – 30.00

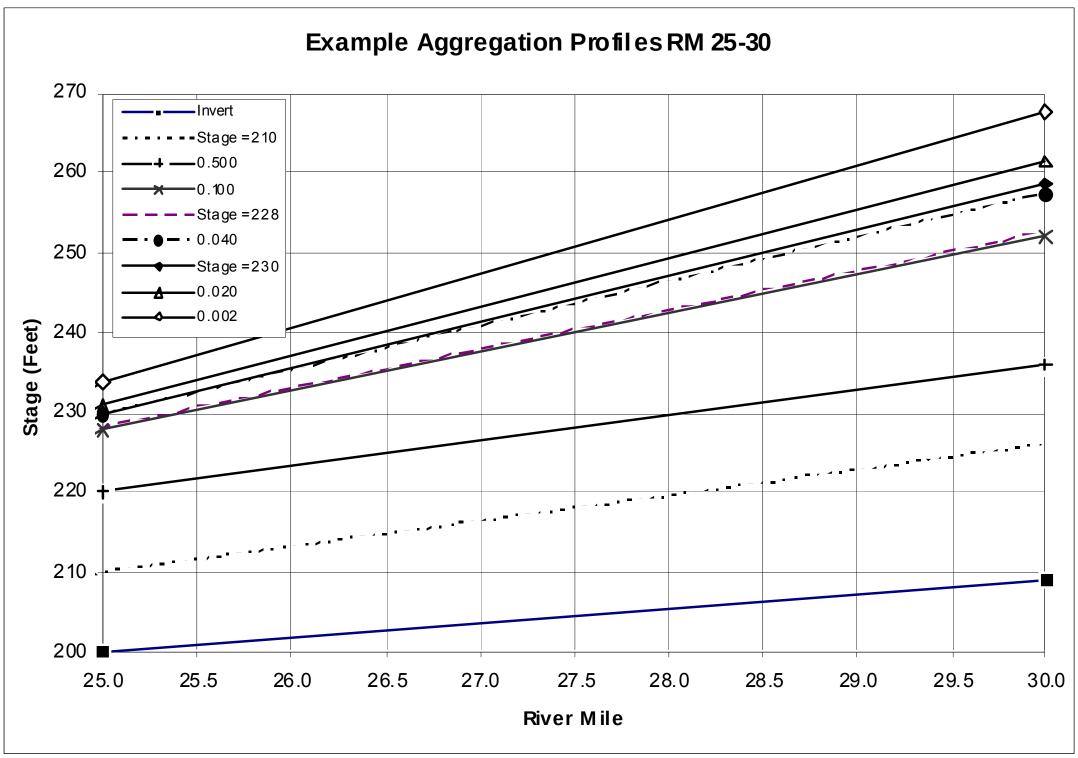


Figure B.9 Selected Aggregation and Water Surface Profiles RM 25.00 – 30.00

Table B.9
Stage-Damage Without Uncertainty for Structure R003

Structure: R0003								
Stream: Sliver Creek								
Reach: SC 2R								
Category: SF Residential								
Address:								
City:								
State:								
Index	**WS Elev @ Index**	**WS Elev @ Structure**	**Nominal Depth**	**Mean Depth**	**Structure Damage**	**Content Damage**	**Other Damage**	**Total Damage**
1	204.00	220.00	-32.00	-32.00	$0.00	$0.00	$0.00	$0.00
2	206.00	222.00	-30.00	-30.00	$0.00	$0.00	$0.00	$0.00
3	208.00	224.00	-28.00	-28.00	$0.00	$0.00	$0.00	$0.00
4	210.00	226.00	-26.00	-26.00	$0.00	$0.00	$0.00	$0.00
5	212.00	228.00	-24.00	-24.00	$0.00	$0.00	$0.00	$0.00
6	214.00	230.00	-22.00	-22.00	$0.00	$0.00	$0.00	$0.00
7	216.00	232.00	-20.00	-20.00	$0.00	$0.00	$0.00	$0.00
8	218.00	234.00	-18.00	-18.00	$0.00	$0.00	$0.00	$0.00
9	220.00	236.00	-16.00	-16.00	$0.00	$0.00	$0.00	$0.00
10	222.00	239.64	-12.36	-12.36	$0.00	$0.00	$0.00	$0.00
11	224.00	243.27	-8.73	-8.73	$0.00	$0.00	$0.00	$0.00
12	226.00	247.30	-4.70	-4.70	$0.00	$0.00	$0.00	$0.00
13	228.00	252.59	0.59	0.59	$6.18	$1.88	$0.00	$8.06
14	230.00	258.69	6.69	6.69	$33.45	$30.07	$0.00	$63.53
15	232.00	264.60	12.60	12.60	$60.40	$42.60	$0.00	$103.00
16	234.00	267.60	15.60	15.60	$71.20	$45.30	$0.00	$116.50
17	236.00	269.60	17.60	17.60	$75.20	$46.30	$0.00	$121.50
18	238.00	271.60	19.60	19.60	$79.20	$47.30	$0.00	$126.50
19	240.00	273.60	21.60	21.60	$80.00	$47.50	$0.00	$127.50
20	242.00	275.60	23.60	23.60	$80.00	$47.50	$0.00	$127.50
21	244.00	277.60	25.60	25.60	$80.00	$47.50	$0.00	$127.50
22	246.00	279.60	27.60	27.60	$80.00	$47.50	$0.00	$127.50
23	248.00	281.60	29.60	29.60	$80.00	$47.50	$0.00	$127.50
24	250.00	283.60	31.60	31.60	$80.00	$47.50	$0.00	$127.50
25	252.00	285.60	33.60	33.60	$80.00	$47.50	$0.00	$127.50
26	254.00	287.60	35.60	35.60	$80.00	$47.50	$0.00	$127.50
27	256.00	289.60	37.60	37.60	$80.00	$47.50	$0.00	$127.50
28	258.00	291.60	39.60	39.60	$80.00	$47.50	$0.00	$127.50
29	260.00	293.60	41.60	41.60	$80.00	$47.50	$0.00	$127.50
30	262.00	295.60	43.60	43.60	$80.00	$47.50	$0.00	$127.50

table to the file *FDA_SDmg.out* if the trace option is set to ten or greater. In this example, the "mean depth" and the "nominal depth" are the same because there is no uncertainty in the economic functions. Some of the following narrative describes results for the highest aggregation stage. Table B.9 lists results for all stages.

(1) Get Structure Information
Retrieve structure data from the database. Includes first floor stage, value of structure, contents, and other, etc. Table B.6 lists some of the sample structure information.

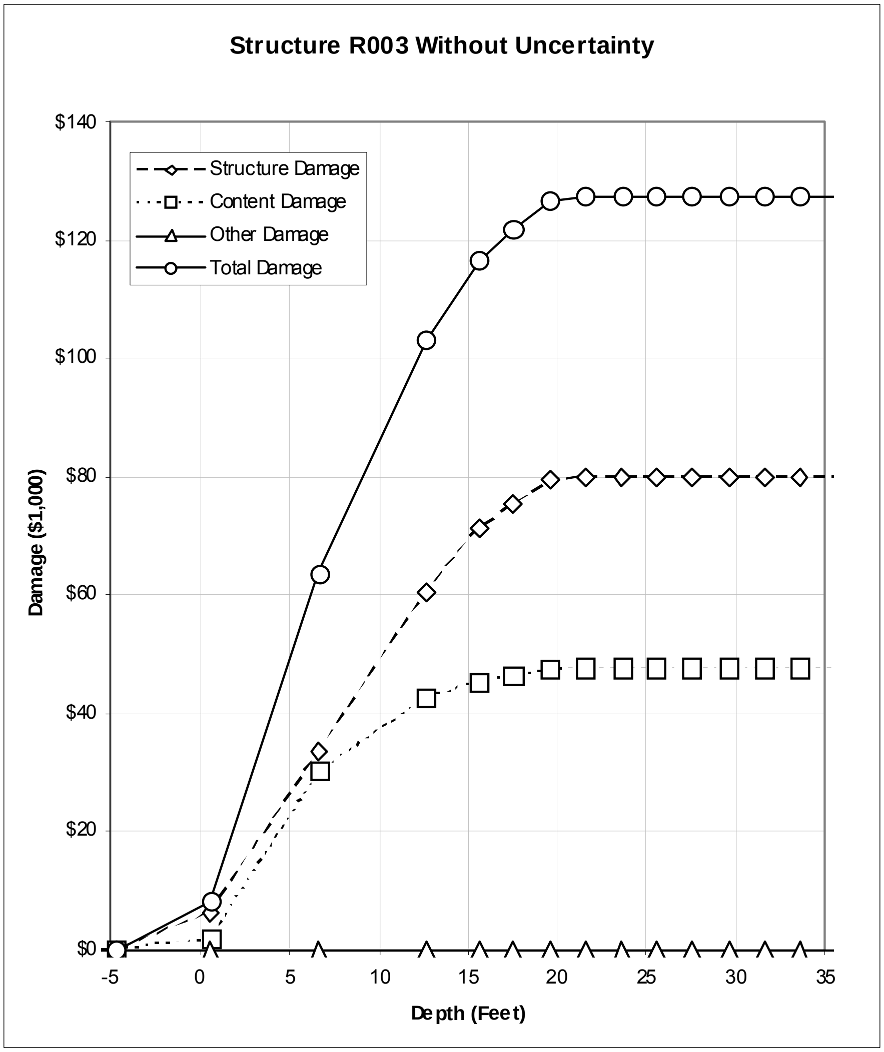


Figure B.10 Stage-Damage Without Uncertainty for Structure R003

(2) Get water surface profiles for the structure's stream
Each structure is assigned a stream. The profiles for the current structure are retrieved from the database. For the example, all structures are on "Silver Creek". If profiles do not exist for Silver Creek, the SID reference flood profile may be used. The example structures all use the water surface profiles as listed in Table B.5.

(3) Select Assumed Water Surface Elevation at the Index Location (Aggregation Stage)
The assumed (or aggregation) stages are listed in Table B.7. The index location is at river mile 25.000. The aggregation stages range from 204.0 to 262.0 feet.

(4) Compute the Assumed Water Surface Stage at the Structure using the aggregation profiles
The assumed (or aggregation stages) are calculated at the structure using the profiles listed in Table B.5. Table B.7 lists the tabulation stages at the index as well as at river mile 20.000 and 30.000 which correspond to structures R001, and R003. For example, an aggregation stage of 236.0 at the index translates into a stage of

269.6 at structure R003. Stages may be interpolated for any river mile between 20.000 and 30.000.

(5) Adjust structure value for price index
The price index is entered as a global value under "File/Study Information". The price index may also be entered by damage category and it will over-ride the global value. If left blank (undefined) the global study price index is used. The price index is simply multiplied by the structure value which is stored in the database to obtain an updated value for calculation purposes. The value in the database is not changed. For this example, the price index is 1.0 and the value for structure R003 is $100k * 1.0 or $100k.

(6) Adjust contents value for price index
Contents value is adjusted in a similar manner to the structure value. The content value must first be determined. For indirect depth-damage functions (using percent damage), it can be computed using the ratio of content-to-structure value entered with the occupancy types. This calculation can be over-ridden by entering a dollar value at individual structures. At the structure level, if the contents value is left blank (undefined), the occupancy code ratio is used. For structures having a direct depth-damage function (damage is in thousands of dollars), the content value is not used for calculations since damage is computed directly from the depth-damage function.

(7) Adjust "other" value for price index
Other value is computed in the same fashion as the contents.

(8) Compute depth of flooding (assumed WSP stage minus first floor stage)
The assumed (aggregation) stages computed above are used to determine the depth of flooding. For the example structure R003, the aggregation stage of 236.0 at the index location translates into a stage of 269.6 at the structure which translates into a depth of 17.6 feet (first floor stage is 252.0 feet).

(9) Compute percent damage to structure from depth of flooding and depth-damage function
The percent structure damage is computed using the depth of flooding (17.6 feet) from step 8 and the depth-percent damage function from occupancy type "SF OS NB". The resulting percent structure damage for a depth of 17.6 feet is 75.2%. FDA does not extrapolate depth-damage functions for depths beyond the defined depth range. For example, the maximum structural damage is 80% of the structure value.

(10) Compute percent damage to contents from depth of flooding and depth-damage function
The percent contents damage is computed in a manner similar to that for structure damage.

(11) Compute percent damage to other from depth of flooding and depth-damage function
The percent other damage is computed in a manner similar to that for structure damage.

(12) Compute structure damage (structure value times percent damage)
The structure damage is computed using the depth of flooding (17.6 feet) from step 8 and the structure value ($100k) from step 5 and the percent damage (75.2%) for the depth of flooding from occupancy type "SF OS NB" from step 9. The resulting damage is: $100k * 0.752 = $75.2k

(13) Compute contents damage (contents value times percent damage)
The contents damage is computed in a manner similar to that for structure damage.

(14) Compute other damage (other value times percent damage)
The other damage is computed in a manner similar to that for structure damage.

(15) Accumulate the damage for structure, contents and other.
The structure, contents, and other damage is accumulated for the selected stream-reach, and category. When all calculations are complete, the results are stored in the database for the calculation plan and year and are stored separately for each stream-reach, damage category, and type (structure, contents, other, and total).

B.4 Computing Stage-Damage at One Structure with Uncertainty

B.4.1 Overview

This section describes the calculation of stage-damage for structures whose economic parameters have uncertainty. The calculations are similar to those when there is no uncertainty except that one or more parameters or functions are sampled. When there is no uncertainty, calculations are done only once for each assumed (aggregation) stage. When uncertainty is included, the calculations must be performed repetitively for each assumed water surface stage (and associated depth of flooding). Figure B.11 depicts the calculation procedures for one structure with uncertainty. Although similar to Figure B.7, Figure B.11 not only reflects risk analysis computations but also depicts the calculation loop for all aggregation ordinates as well as multiple iterations when a single structure record represents multiple, identical structures.

B.4.2 Risk Analysis Calculations

The repetitive risk analysis calculations are done within the simulation loop. The model makes 100 simulations at each stage, but the user can change this using the parameter, "Compute Stage-Damage". The user may specify uncertainty parameters for the first floor stage, structure value, content value, other value, and damage in the depth-damage functions. Each of the uncertainties is defined by one or more parameters and an associated distribution. Allowable distributions include normal, log-normal, and triangular. For example, to describe the uncertainty in the first

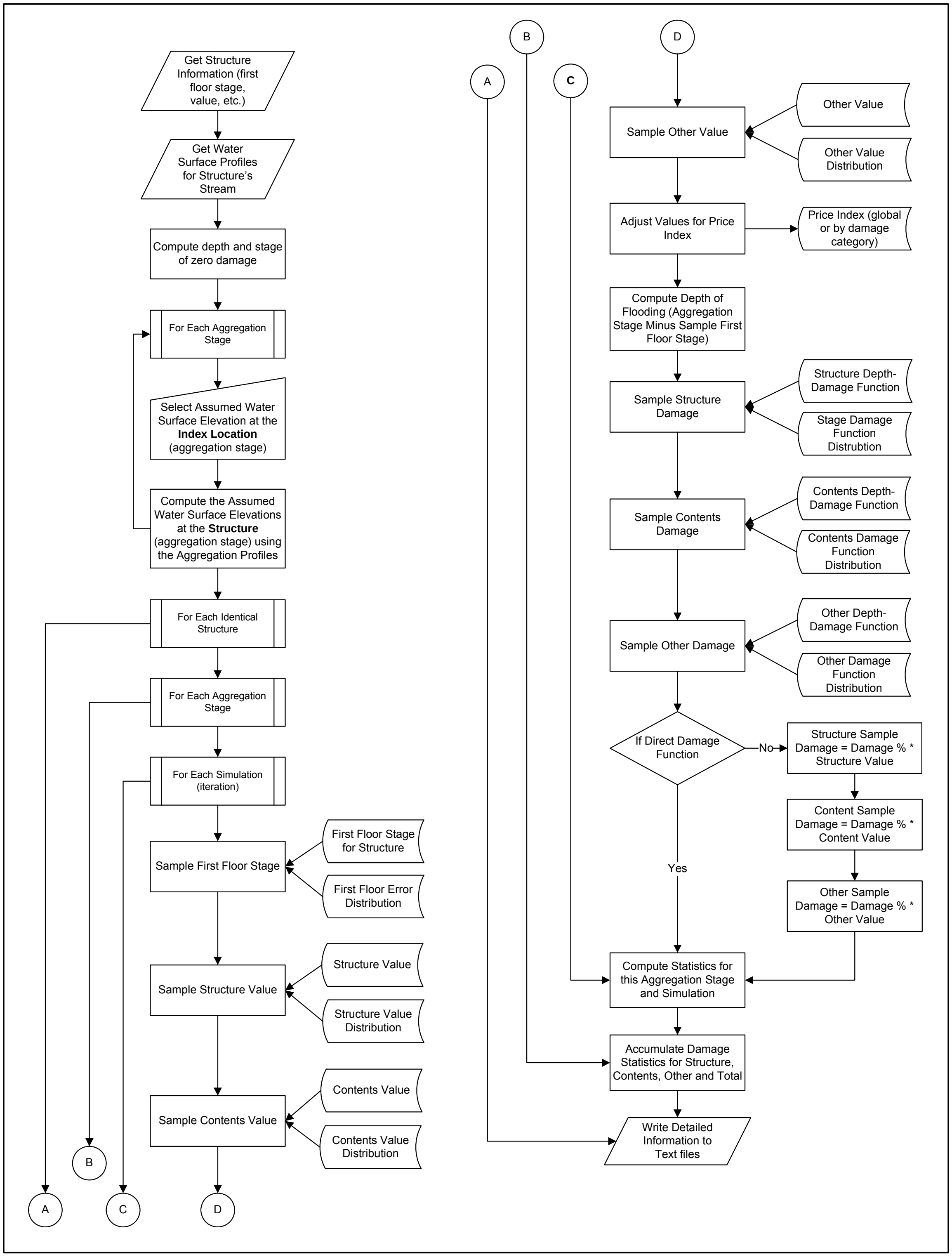


Figure B.11 Calculating Stage-Damage Without Uncertainty for One Structure

floor stage, you may define a normal distribution with a standard deviation of 0.3 feet. For each simulation, the model samples this first floor distribution to derive a simulated first floor stage with error. Similar procedures are used for values (structure, content, other) and the damage in the depth-damage functions.

B.4.3 Identical Structures

The calculation loop for identical structures allows you to enter data for one structure but specify that it represents several structures which have identical characteristics (first floor stage, value, occupancy type, etc.). A user can enter an integer which is greater than one for the parameter "Number of Structures". The model takes one structure record and iterates the calculation loop "Number of Structures" times. Each iteration is treated as a new structure with full Monte-Carlo simulation but uses the same structure information such as first floor stage, structure value, occupancy type, etc.

B.4.4 Detailed Description of Stage-Damage Calculation with Uncertainty

The following section describes in detail the stage-damage calculations depicted in Figure B.11. It is similar to the previous section on calculations without uncertainty. Table B.10 lists the uncertainty parameters for this example. Table B.11 lists results for structure R003.

Table B.10
Uncertainty Parameters for Example Problem

Parameter	Distribution	Std. Dev.
First Floor Stage	Normal	0.3 feet
Structure Value	Normal	10%
Contents Value Ratio	Normal	20%
Damage in Depth-Damage Function	Normal	5%

FDA writes this table to the file *FDA_SDmg.out* if the trace option is set to ten or greater. In this example, the "mean depth" and the nominal depth are not the same because there is uncertainty in the first floor stage. The nominal depth is the depth when no uncertainty is used whereas the mean depth is the calculated mean depth after Monte-Carlo simulations. Some of the narrative below describes results for the highest aggregation stage. Figure B.12 depicts the computed stage-damage with uncertainty function for structure R003.

(1) Get structure information.
Retrieve structure data from the database. This includes first floor stage, value of structure, contents, and other, etc. Table B.6 lists some of the sample structure information.

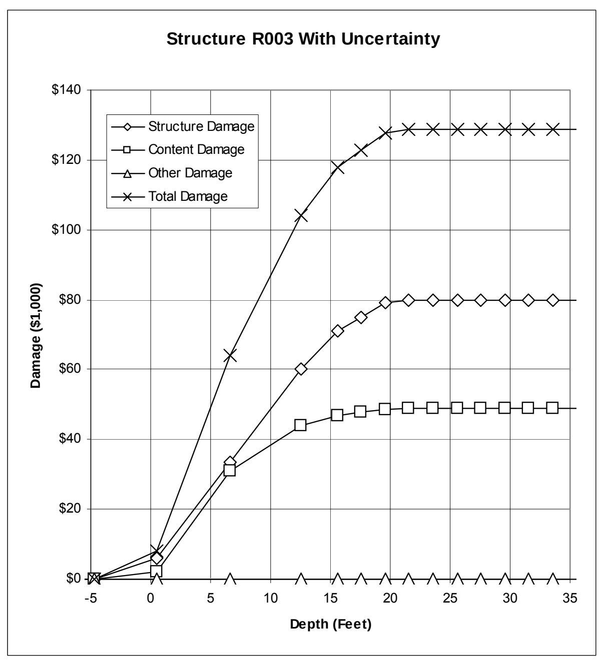


Figure B.12 Stage-Damage With Uncertainty for Structure R003

Table B.11
Stage-Damage Without Uncertainty for Structure R003

Structure: R0003								
Stream: Sliver Creek								
Reach: SC 2R								
Category: SF Residential								
Address:								
City:								
State:								
Index	**WS Elev @ Index**	**WS Elev @ Structure**	**Nominal Depth**	**Mean Depth**	**Structure Damage**	**Content Damage**	**Other Damage**	**Total Damage**
1	204.00	220.00	-32.00	-32.00	$0.00	$0.00	$0.00	$0.00
2	206.00	222.00	-30.00	-30.00	$0.00	$0.00	$0.00	$0.00
3	208.00	224.00	-28.00	-28.00	$0.00	$0.00	$0.00	$0.00
4	210.00	226.00	-26.00	-26.00	$0.00	$0.00	$0.00	$0.00
5	212.00	228.00	-24.00	-24.00	$0.00	$0.00	$0.00	$0.00
6	216.00	230.00	-22.00	-22.00	$0.00	$0.00	$0.00	$0.00
7	215.00	232.00	-20.00	-20.00	$0.00	$0.00	$0.00	$0.00
8	218.00	234.00	-18.00	-18.00	$0.00	$0.00	$0.00	$0.00
9	220.00	236.00	-16.00	-16.00	$0.00	$0.00	$0.00	$0.00
10	222.00	239.64	-12.36	-12.36	$0.00	$0.00	$0.00	$0.00
11	224.00	243.27	-8.73	-8.73	$0.00	$0.00	$0.00	$0.00
12	226.00	247.30	-4.70	-4.70	$0.00	$0.00	$0.00	$0.00
13	228.00	252.59	0.59	0.59	$6.18	$1.88	$0.00	$8.06
14	230.00	258.69	6.69	6.69	$33.45	$30.07	$0.00	$63.53
15	232.00	264.60	12.60	12.60	$60.40	$42.60	$0.00	$103.00
16	234.00	267.60	15.60	15.60	$71.20	$45.30	$0.00	$116.50
17	236.00	269.60	17.60	17.60	$75.20	$46.30	$0.00	$121.50
18	238.00	271.60	19.60	19.60	$79.20	$47.30	$0.00	$126.50
19	240.00	273.60	21.60	21.60	$80.00	$47.50	$0.00	$127.50
20	242.00	275.60	23.60	23.60	$80.00	$47.50	$0.00	$127.50
21	244.00	277.60	25.60	25.60	$80.00	$47.50	$0.00	$127.50
22	246.00	279.60	27.60	27.60	$80.00	$47.50	$0.00	$127.50
23	248.00	281.60	29.60	29.60	$80.00	$47.50	$0.00	$127.50
24	250.00	283.60	31.60	31.60	$80.00	$47.50	$0.00	$127.50
25	252.00	285.60	33.60	33.60	$80.00	$47.50	$0.00	$127.50
26	254.00	287.60	35.60	35.60	$80.00	$47.50	$0.00	$127.50
27	256.00	289.60	37.60	37.60	$80.00	$47.50	$0.00	$127.50
28	258.00	291.60	39.60	39.60	$80.00	$47.50	$0.00	$127.50
29	260.00	293.60	41.60	41.60	$80.00	$47.50	$0.00	$127.50
30	262.00	295.60	43.60	43.60	$80.00	$47.50	$0.00	$127.50

(2) Get water surface profiles for the structure's stream.
Each structure is assigned a stream. The water surface profiles for the current structure are retrieved from the database. For the example, all structures are on *Silver Creek*. If water surface profiles do not exist for *Silver Cree*k, the SID reference flood profile may be used. The example structures all use the water surface profiles as listed in Table B.5.

(3) Compute depth and stage of zero damage.
The model looks at the depth-damage functions (structure, content, and other) and the optional **Beginning Damage Depth** to determine the highest depth of zero damage. For the example structure occupancy type, this is at a depth of -1 feet. Normally, the **Beginning Damage Depth** is left blank (undefined). It may be defined

by individual structure if the damage functions are truncated at some depth. For example, this typically occurs for houses with basements where the damage function may start at a depth of -8 feet but water may not enter the basement until it reaches a depth of -1 foot. If some barrier prevented water from reaching structure R003 before a depth of 1 foot above the first floor, then you would define the **Beginning Damage Depth** as +1.0 foot and FDA would set the damage to zero for all aggregation depths of 1 foot or less during the Monte-Carlo simulations. The corresponding stage of zero damage is computed during the simulations as the sum of the first floor stage with error and the **Beginning Damage Depth**.

(4) Select assumed water surface elevation at the index location (aggregation stage).
The assumed (or aggregation) stages are listed in Table B.7. The index location is at river mile 25.000. The aggregation stages range from 204.0 to 262.0 feet.

(5) Compute the assumed water surface stage at the structure using the aggregation profiles.
The assumed (or aggregation stages) are calculated at the structure using the profiles listed in Table B.5. Table B.7 lists the tabulation stages at the index as well as at river mile 20.000 and 30.000 which correspond to structures R001, and R003. For example, an aggregation stage of 236.0 at the index translates into a stage of 269.6 at structure R003. Stages may be interpolated for any river mile between 20.000 and 30.000.

(6) For each identical structure, process the following steps:
Normally, the subsequent steps are processed once. If the **Number of Structures** is set to a value greater than one (1), the current structure is processed **Number of Structures** times to facilitate a crude sampling of structures. For example, if processed ten times, it is equivalent to entering ten identical structures.

(7) For each aggregation stage.
The following steps are repeated for each assumed (aggregation) stage. The stages are listed in Table B.7.

(8) For each simulation (iteration).
The following steps are repeated for each Monte-Carlo simulation. The model currently does 100 simulations, this can be adjusted.

(9) Sample first floor stage.
The first floor stage with uncertainty is computed from the first floor stage, the uncertainty distribution and the uncertainty parameters. The uncertainty data is defined with the occupancy types (indirect depth-percent damage functions) or the structure (direct depth-dollar damage functions). The uncertainty parameters are in the same units as the first floor stage. For structure R003 (first floor stage of 252.0), the uncertainty in the first floor stage is modeled using the normal distribution with a standard deviation of 0.3 feet. If a sampled error in the first floor stage was one standard deviation from the median, the sampled first floor stage would be 252.3 feet.

(10) Sample structure value.
The structure value with uncertainty is computed from the structure value, the uncertainty distribution, and the uncertainty parameters. The uncertainty data is

defined with the occupancy types. If using direct depth-dollar damage functions, the structure value is not sampled because it is built into the uncertainty of the damage function. The uncertainty parameters are entered in the percent of structure value. TableA.10 lists the uncertainty parameters for the example data. For structure R003 (value $100,000; occupancy code structure value error of 10%) a simulation error of one standard deviation would result in a sample structure value of $110,000 ($100,000 + $10,000 * 1std.dev.). The use of uncertainty in percent allows structures of different values to use the same occupancy type and still maintain reasonable errors about the median value. For example, a $200,000 house using the same example occupancy type would have a computed standard deviation of error of $20,000.

(11) Sample contents value.

Contents value is sampled in a similar manner to the structure value. The content value must first be determined. For indirect depth-damage functions (using percent damage), it can be computed using the ratio of content-to-structure value entered with the occupancy types. This calculation can be over-ridden by entering a dollar value at individual structures. At the structure level, if the contents value is left blank (undefined), the occupancy code ratio is used to compute contents value from the structure value. If using direct depth-dollar damage functions, the contents value is not sampled because it is built into the uncertainty of the damage function. The uncertainty parameters are entered in the percent of contents-to-structure value ratio. The occupancy code for this example has a ratio of 50% for contents-to-structure value ratio. For structure R003 (contents value = $100,000 times 50% = $50,000; occupancy code has a contents-to-structure value ratio error of 20%) a simulation error of one standard deviation would result in a sample contents value of $60,000 (error = $50,000 * (.5 +.5 * .2 * 1 std.dev.)). The use of uncertainty in percent allows structures of different content value to use the same occupancy type and still maintain reasonable errors about the median value. For example, a $200,000 house using the same example occupancy type would have a computed standard deviation of error of $20,000.

(12) Sample other value.

Other value is sampled in the same fashion as the contents.

(13) Adjust values for price index

The price index is entered as a global value and the price index may also be entered by damage category and it will override the global value. If left blank (undefined) the global study price index is used. The price index is simply multiplied by the structure, contents, and other values to obtain updated values for calculation purposes. The values in the database are not changed. For this example, the price index is 1.0 and the value for structure R003 is $100k * 1.0 or $100k (no error in structure value). During Monte-Carlo simulation, the price index is multiplied by the values with sampling error.

(14) Compute depth of flooding (aggregation stage minus sample first floor stage).

The assumed (aggregation) stages computed above and the sampled first floor stage are used to determine the depth of flooding. For the example structure R003, the aggregation stage of 236.0 at the index location translates into a stage of 269.6 at the structure. If the sampled first floor stage is 252.3, the depth of flooding is 17.3 feet (first floor stage without error is 252.0 feet and with a one standard deviation of error is 252.3 feet).

(15) Sample structure damage.
The sampled structure damage is computed from the sampled depth of flooding, and the sampled depth-damage function. The sampled percent structure damage is computed using the depth of flooding (17.3 feet) from Step 14 and the depth-percent damage function with uncertainty from structure occupancy type ***SF OS NB***. The resulting percent structure damage for a sampled depth of 17.3 feet is 74.6 percent (un-sampled damage function) or 78.3 percent (sampled one standard deviation away from the median damage). The model does not extrapolate depth-damage functions for depths beyond the defined depth range. For this example of structure R003 using the sampled first floor stage (252.3), the sampled structure value ($110,000), and the sampled depth-percent damage function (78.3 percent damage), the structure damage is computed as:

$$\$110,000 * 78.3\% = \$86,130.$$

This can be compared to the same calculation of structure damage without uncertainty which was $75,200. Obviously, it is very rare that the sampled parameters would always be +1 standard deviation away from the median.

The procedure for sampling structures using direct depth-dollar damage functions is the same as for with indirect depth-damage functions with the exception that damage is computed directly from sampled depth and sampled direct depth-damage functions.

(16) Sample contents damage.
The sampled contents damage is computed in a manner similar to that for structure damage.

(17) Sample other damage.
The sampled other damage is computed in a manner similar to that for structure damage.

(18) Compute statistics for this aggregation stage and simulation.
The statistics for the current aggregation stage for all simulations are computed and stored in memory before the aggregation stage is decreased for the next simulations.

(19) Accumulate the damage for structure, contents and other
The structure, contents, and other damage is accumulated in memory for the selected stream, damage reach, and damage category.

(20) Write detailed information to ASCII text files.
When all simulations are completed for the current structure, the model accumulates the current results in memory and writes various levels of calculation results to text files *FDA_SDmg.out* (stage-depth-damage by structure and by damage reach/damage

category), *FDA_StrucDetail.out* (individual structure results in a tab-delimited text file suitable for import), *FDA_SDev.out* (individual structure Monte-Carlo simulation results), and *FDA_SdErrors.out* (structure data errors). These files are described in later sections.

(21) Store results in the database.
When all calculations are complete, the results are stored in the database for the calculation plan and analysis year and are stored separately for each stream, damage reach, damage category, and structure occupancy type (structure, contents, other, and total). The EAD calculations utilize only the total damage for each damage category - not the individual structure, contents and other damage functions.

B.5 Aggregating the Stage-Damage Functions to the Index Location

The process of using either the eight water surface profiles or the SID reference flood water surface profile has been described earlier. Since the calculations are done at each structure at the aggregation stages, the results (both damage as well as statistics for uncertainty calculations) are easily accumulated to the index location. Table B.12 displays the total simulated damage for reach SC 2R. It includes aggregated damage for the three residential structures. Damage categories Commercial, Industrial, and Public do not have damage since only residential structures have been entered in this reach.

Table B.12
Total Stage-Aggregated Damage,
Damage Reach SC 2R

Total Aggregated Damage Matrix.					
Stream: Sliver Creek					
Reach: SC 2R					
	Stage	**Commercial**	**Industrial**	**Public**	**SF Residential**
1	204	0.00	0.00	0.00	0.00
2	206	0.00	0.00	0.00	0.00
3	208	0.00	0.00	0.00	0.00
4	210	0.00	0.00	0.00	0.00
5	212	0.00	0.00	0.00	0.00
6	214	0.00	0.00	0.00	0.00
7	216	0.00	0.00	0.00	0.00
8	218	0.00	0.00	0.00	0.00
9	220	0.00	0.00	0.00	0.00
10	222	0.00	0.00	0.00	0.00
11	224	0.00	0.00	0.00	0.00
12	226	0.00	0.00	0.00	0.04
13	228	0.00	0.00	0.00	20.78
14	230	0.00	0.00	0.00	100.92
15	232	0.00	0.00	0.00	180.52
16	234	0.00	0.00	0.00	219.37
17	236	0.00	0.00	0.00	259.18
18	238	0.00	0.00	0.00	295.81
19	240	0.00	0.00	0.00	322.66
20	242	0.00	0.00	0.00	342.96
21	244	0.00	0.00	0.00	360.14
22	246	0.00	0.00	0.00	372.30
23	248	0.00	0.00	0.00	381.77
24	250	0.00	0.00	0.00	386.38
25	252	0.00	0.00	0.00	386.55
26	254	0.00	0.00	0.00	386.55
27	256	0.00	0.00	0.00	386.55
28	258	0.00	0.00	0.00	386.55
29	260	0.00	0.00	0.00	386.55
30	262	0.00	0.00	0.00	386.55

APPENDIX C

Monte Carlo Simulation

C.1 Overview

Monte Carlo simulation (Davis and Rabinowitz 1967) is used in HEC-FDA to derive the expected annual damage corresponding to a particular plan/analysis year for a damage reach. The expected annual damage (EAD) is the mean damage obtained by integrating the damage exceedance probability curve for the damage reach. The damage-exceedance probability function is obtained from the discharge-exceedance probability, stage-discharge, and damage-stage functions derived at a damage reach index location. The inclusion of uncertainty for these variables requires a numerical integration approach be applied. Without uncertainty, the damage-exceedance probability curve can be obtained directly without resorting to numerical simulation approaches.

Monte Carlo simulation is the numerical integration approach. It relies on an exceedance probability analysis of samples of the contributing random variables obtained from the generation of random numbers. Although inelegant, the technique is computationally efficient in comparison with other techniques as the number of contributing variables exceeds about five.

C.2 Numerical Integration with Monte Carlo Simulation

Expected annual damage is the probability weighted average of all possible peak annual damages. It is also termed the mean or expected annual damage. As a simple example of computing a probability weighted average, consider the rolling of a die. The probability of obtaining any outcome of any roll of a die is 1/6, since the probability of obtaining any face of the die is considered equally likely (at least if the die is fair). The probability weighted average is then computed as:

$$\sum_{i=1}^{i=6} d_i p_i = \frac{1}{6}(1+2+3+4+5+6) = 3.5 \qquad (1)$$

where d_i is the possible outcome of rolling a die, and pi is the probability of the outcome. The probability weighted average or expected outcome of 3.5 obtained in equation (1) could be obtained by performing a die rolling experiment. The experiment would just involve many trials of rolling the die and averaging the outcome. As the number of trials becomes large the average obtained will equal 3.5.

Performing trials with the die is an application of a Monte Carlo simulation to obtain an average. In rolling the die, random integers are obtained in the inclusive interval 1 to 6, and a statistical analysis of the outcome is performed to obtain an average. Consequently, Monte Carlo simulation or application of Equation 1, are equivalent procedures for obtaining the mean or expected value.

Other statistical characteristics of rolling a die could be obtained, such as by performing a class category analysis on the outcomes to determined the probability of obtaining any outcome. If this were done, the probability of obtaining any die face in a single trial would be found to be 1/6.

This same type of sampling experiment can be performed to obtain EAD. Computation of EAD is somewhat more difficult in that damage is a continuous random variable, unlike the outcome of rolling a die, which has discrete outcomes. Consequently, damage probability is either stated for an interval, or more typically as, the probability of exceeding a particular value. These probabilities are defined by the damage exceedance probability function or equivalently, the cumulative distribution function as defined by:

$$P[D > d] = F(D) = \int_{d}^{\infty} f(D) dD \qquad (2)$$

where D is the annual damage, F(D) is a function defining the damage exceedance probability curve, f(D) is the probability density function (units of probability per increment of damage), and P[D>d] is read as "the probability that D exceeds d."

The probability density function can be used to calculate the EAD or equivalently the probability weighted average damage by performing the following numerical integration:

$$EAD = \int_{0}^{\infty} Df(D) dD \sim \sum_{i=1}^{i=N} D_i \Delta_p \qquad (3)$$

where the integral in equation (3) is approximated by a sum as in equation (1), Δp is the probability of damage being in an interval, D_i is the midpoint damage of this interval, and N is the number of intervals (Figure C.1). The approximation turns the integration of a continuous random variable into that of a discrete variable much as in the computation of the average outcome for rolling a die shown in Equation 1. The difference between the equations is that Equation 1 is exact and the probability is for a discrete outcome; whereas, Equation 3 is approximate and Δp is an interval probability.

The numerical integration is necessary because the damage-exceedance probability function is not defined by a continuous analytic function making an analytic integration impossible. Given that an exact analytic value cannot be obtained, how good is the approximation provided in Equation 3? The approximation can be made as accurate as possible by decreasing the interval Δp, or equivalently, increasing the number of intervals shown in Figure C.1.

Recognizing that equal probability increments implies that Δp=1/N, where N is the number of increments in Figure B.1, Equation 3 can be rewritten as:

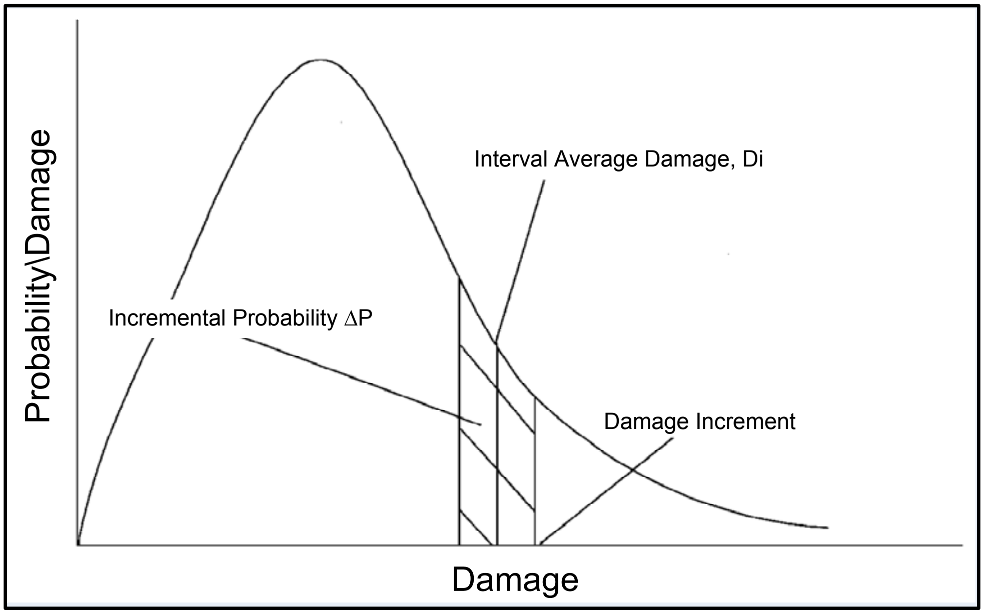


Figure C.1 Numerical Integration of Probability Density Function to Obtain EAD

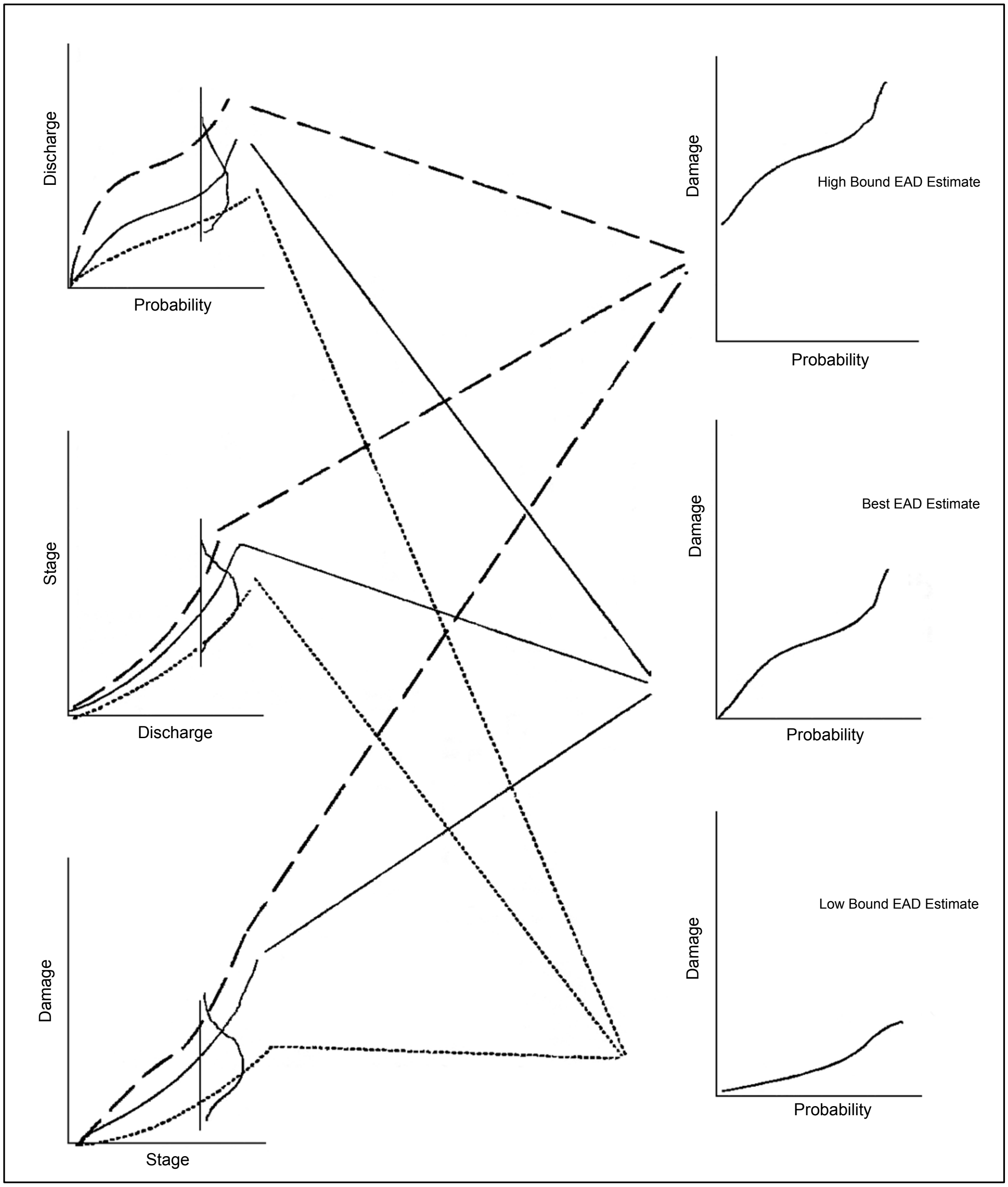
$$EAD = \sum_{i=1}^{i=N} D_i \Delta p = \sum_{i=1}^{i=N} \frac{D_i}{N} \qquad (4)$$

C.3 Computing Expected Annual Damage, Exceedance Probability, and Event Probabilities

The inclusion of uncertainty in estimates of the variable contributing to damage makes it possible to obtain both a best estimate of expected annual damage and a distribution of possible values about this best estimate. Additionally, an expected set of exceedance probability functions and event conditional stages can be computed as a consequence of providing these estimates of uncertainty.

The relationship between estimation uncertainty and the distribution of EAD can be understood by considering a sensitivity analysis application to computing EAD with a flow-exceedance probability curve, rating curve and stage-damage relationship as shown in Figure C.2. The figure shows that high-bound, low-bound and best estimates of each relationship are combined to obtain a corresponding range in estimates of EAD. This range in estimates could be thought of as defining a rough distribution of possible EAD estimates. The difficulty with this sensitivity analysis approach is that the relative likelihood of the range in estimates is not known.

Monte Carlo simulation is used to improve on the sensitivity analysis by integrating all possible random occurrences of the contributing relationships as shown in Figure C.3. This differs from the basic Monte Carlo application described in the previous section by obtaining a random sample of relationships or random functions instead of obtaining a random sample of individual values. The algorithm used to obtain random samples of each relationship is described later.



FigureC.2 EAD Computation Sensitivity Analysis

The Monte Carlo algorithm used to obtain the distribution and best estimate of EAD, expected exceedance probability curves and event related conditional stage exceedance probability proceeds as follows:

1. **Obtain a random sample of the contributing relationships**
   Each relationship is sampled to obtain a single realization of the discharge-exceedance probability, the stage-discharge (rating) and the stage-damage functions.

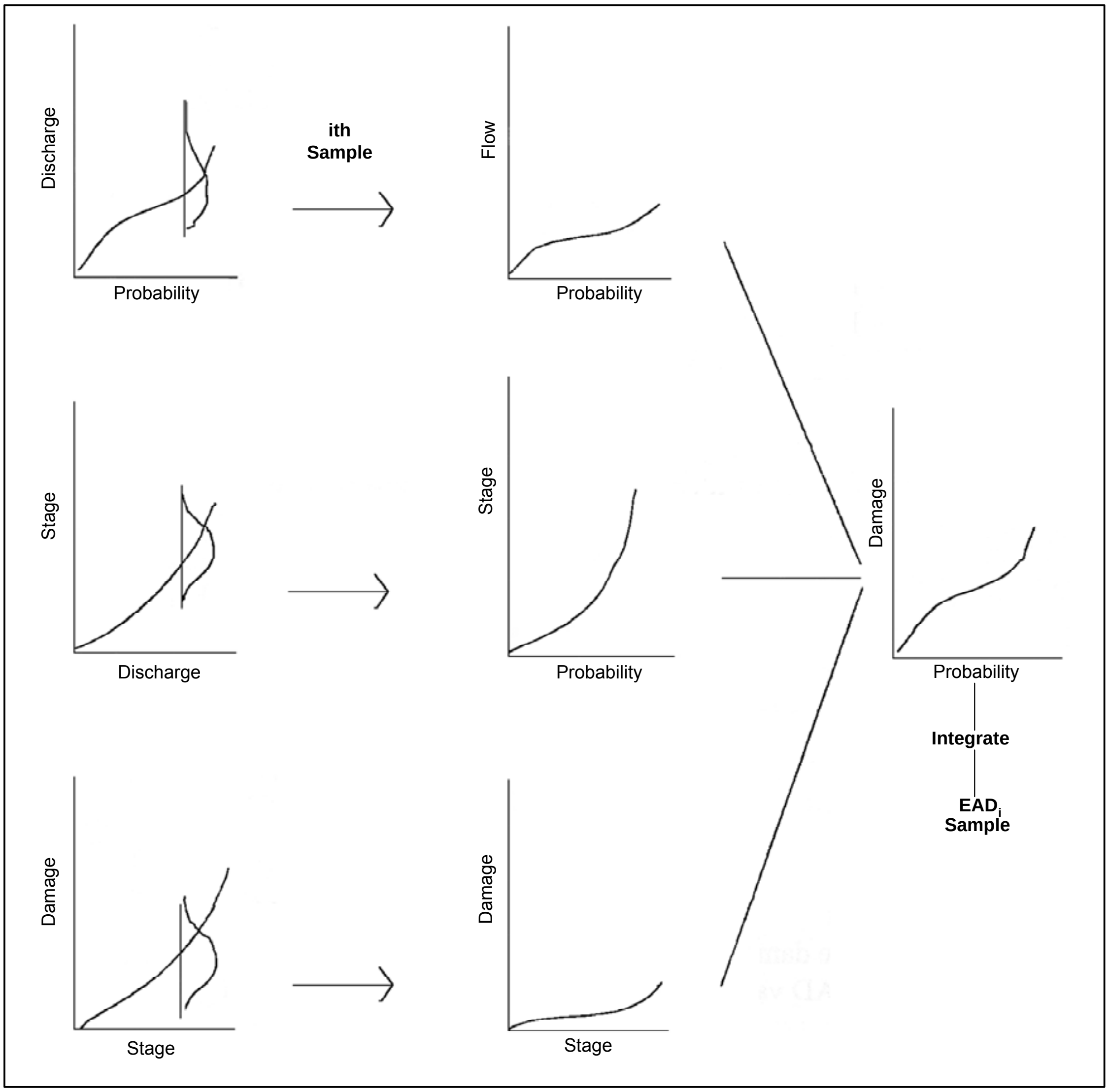


Figure C.3 Monte Carlo Simulation Algorithm for Estimating EAD

2. **Compute exceedance probability curves**
Compute the stage-exceedance probability function by using the rating curve to transform the sample discharge-exceedance probability function into a stage-exceedance probability curve; and, compute the damage exceedance probability function by using the sample stage-damage function to transform the stage-exceedance probability curve into a damage-exceedance probability function.

3. **Save intermediary results for computing expected exceedance probability curves**
Intermediary results are saved for the computation of expected exceedance probability functions by adding discharges, stages and damages for specified probabilities to values summed for previous simulation.

4. **Save intermediary results for computing event conditional stage probabilities**
Event conditional stages are saved for later estimation of conditional stage exceedance probabilities. The stages are conditional on specified exceedance probabilities (e.g., conditional on the 0.1, 0.02, 0.01 stage being exceeded). The stage for each of the events

of interest is saved in a stage class interval. For example, consider that a stage of 21.56 corresponds to the 0.01 exceedance probability for the sample stage exceedance probability curve obtained in Step 2. This value is saved in a predetermined class interval that may have minimum and maximum limits of respectively, 21.0 and 22.0.

5. **Save intermediary results for computation of EAD**
The EAD for the sample contributing relationships is computed by integrating the damage exceedance probability curve. This value is both added to a sum of EAD values from previous iterations and saved in a damage class interval.

6. **Repeat sampling Steps 1 through 5**
Additional samples of exceedance probability curves and EAD are obtained by repeating Steps 1 through 5. Sampling ceases when an accuracy criterion is met.

7. **Compute expected exceedance probability curves**
Divide the summed values obtained in Step 3 for discharge, stage and damage for each exceedance probability by the number of samples.

8. **Compute conditional event stage distributions**
The process in Step 4 of placing stages in class intervals results in an exceedance probability histogram of stages for each exceedance probability event of interest. Table C.1 provides an example of some possible results for the 0.01 exceedance probability event. As shown in the table, the exceedance probability histogram is converted into an event conditional exceedance probability function.

Table C.1
Calculating Event Conditional Stage Exceedance Probability from Monte Carlo Simulation Frequencies

Lower Limit Stage	Upper Limit Stage	Frequency	Cumulative Frequency	Cumulative Probability	Exceedance Probability
<21.0	21.0	200	200	0.01	0.99
21.0	22.0	5000	5200	0.26	0.74
22.0	23.0	10000	15200	0.75	0.25
23.0	24.0	5000	20200	0.99	0.01
24.0	25.0	100	20300	1.0	0.0
25.0	25.0>	0	20300	1.0	0.0

9. **Compute best estimate of EAD and Distribution of EAD**
The best estimate of EAD is computed as the average of the samples summed in Step 5. The class interval exceedance probabilities for EAD are converted to an exceedance probability distribution using the same procedure for event conditional stages (Table C.1).

In performing this simulation, only the stage versus total damage relationship is used to obtain the damage exceedance probabilities function and corresponding EAD. Damage-exceedance probability functions and EAD for damage categories are proportioned in the same ratio as the traditional (no uncertainty) category damage is to the tradition total damage values.

C.4 Monte Carlo Simulation Options for Calculating EAD

The Monte Carlo simulation can be expanded to include other contributing relationships in the calculation of EAD. Table C.2 describes the options for including other relationships. Notice that some relationships involve uncertainty calculations and others (levee effects and interior stage versus exterior stage relationships) are specified without uncertainty. The

Table C.2
Contributing Relationships Used in EAD Calculation

Contributing Relationship	Uncertainty Distribution
Flow/stage frequency curve	yes
Flow transform	yes
Rating curve	yes
Wave overtopping of flood wall or levee	yes
Levee impact on damage	no
[1]Exterior versus interior stage	no
Stage versus damage	yes

[1] Used to directly convert exterior river stage, interior levee failure stage, or with wave overtopping

inclusion of additional relationships does not require any new aspect of performing the simulation except to require the creation of additional random samples of another relationship. For example, Figure C.4 displays the additional step of using the flow transform to convert a reservoir inflow-exceedance probability curve to a regulated exceedance probability curve.

C.5 Sampling Algorithm for Numeric Integration

C.5.1 Overview

Application of Monte Carlo simulation requires a method for producing random samples and criteria for determining the number of samples needed to obtain a numerical integration with pre-specified accuracy. The algorithms (previously described) produce random samples of the contributing relationships that are combined to obtain samples of EAD, exceedance probability functions and event conditional stage probabilities. This sampling depends on the algorithm for generating random numbers. The generation of random numbers and the random sampling of contributing relationships is the means by which Monte Carlo simulation performs a numerical integration. As previously discussed, the numerical integration accuracy increases with the number of simulations. The criteria used to determine the number of simulations for a desired level of accuracy is described in the next section. The related problem of obtaining a numerically accurate integration of the damage-exceedance probability function is also discussed later.

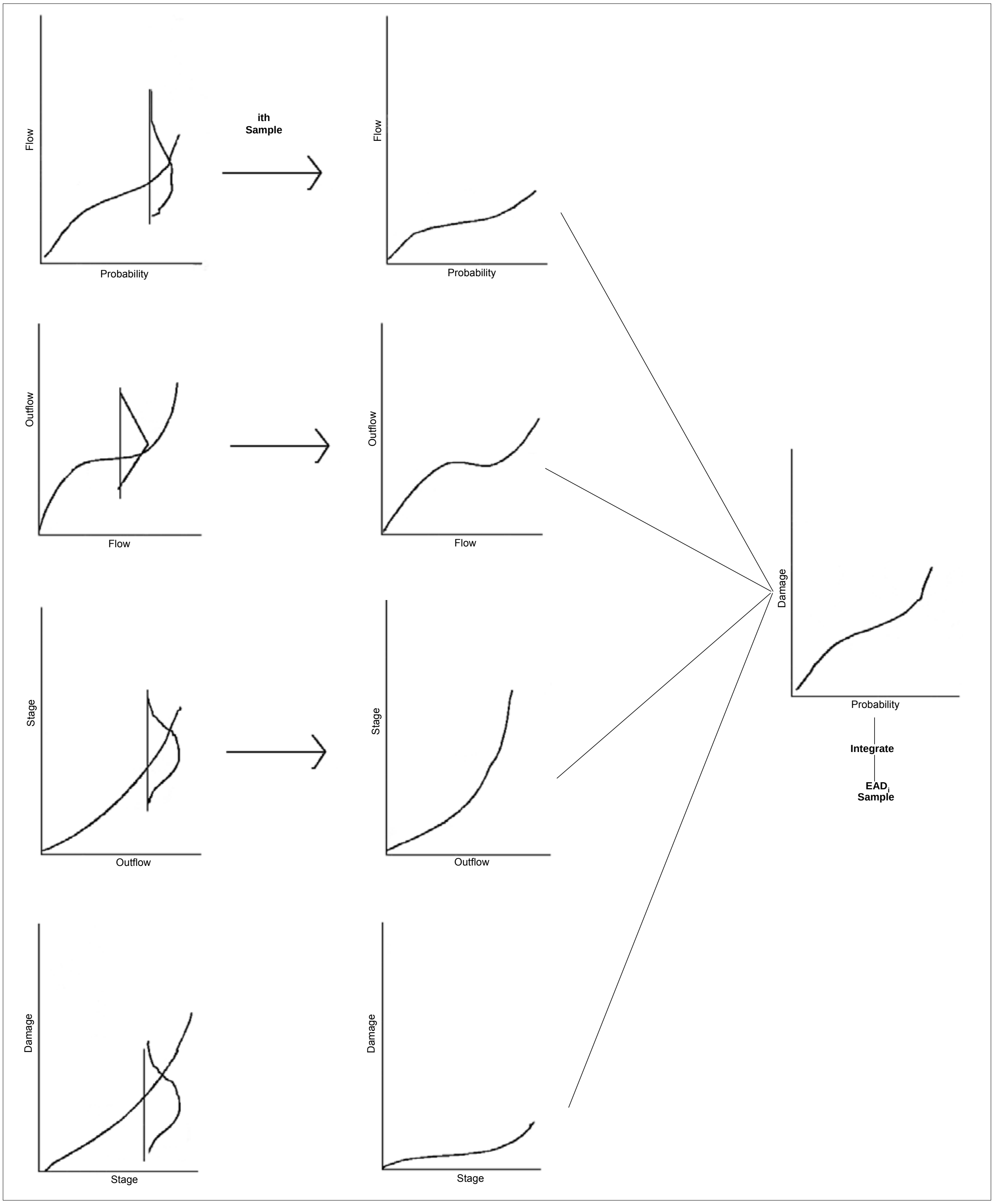


Figure C.4 Adding Computation of Regulated Outflow to Monte Carlo Algorithm for Computing EAD

C.5.2 Sampling from the Log-Pearson III Distribution

Random samples of a log-Pearson III (LPIII) exceedance probability curve are obtained from random samples of the mean and standard deviation of the logarithm of the flow, computing a log-normal relationship and adjusting for the skew of the distribution. This scheme produces the same sampling variability inherent in the calculation of confidence limits and expected probability as described in Bulletin 17B (IACWD, 1982), the federal guidelines for performing flood-flow exceedance probability analysis.

The random sampling is based on a Bayesian statistical approach for assessing uncertainty (Stedinger, 1983). A goal of Bayesian estimation is to develop the distribution of possible population parameters (the posterior distribution) by combining statistics of the observed sample (e.g., observed stream flows), and other information on the probable range of population parameters (the prior distribution). In this instance, the prior distribution is based on the assumption that an equally likely set of parent populations could have produced the estimated sample mean, standard deviation and resulting log-normal distribution. The resulting posterior distribution of the population mean and standard deviation is given by:

$$P[\mu > m] = F(\mu) = \Phi\left(\overline{X}, \frac{S}{\sqrt{N}}\right) \tag{5}$$

$$P[\sigma^2 > s] = F(\sigma^2) = \frac{(N-1)S^2}{\chi^2_{(N-1)}} \tag{6}$$

where $\overline{X}$ and S are respectively the sample mean and standard deviation of the logarithm of flow values obtained from a record length of N years, μ is the population mean, Φ( ) is the normal distribution defined by the parameters shown, σ is the population standard deviation, and $\chi^2_{(N-1)}$ is the chi-square distribution with N-1 degrees of freedom. Random estimates of the log-normal distribution are obtained by generating random estimates of normal and chi-square numbers, applying Equations 5 and 6 to obtain μ and σ and computing the distribution (Figure C.5).

This scheme for computing uncertainty does not account for the effect of shape or skew that is a characteristic of the LPIII distribution. This omission of the sampling uncertainty in skew is in keeping with the approach taken in the Bulletin 17B guidelines where sampling error is only estimated for a log-normally distributed variate. Consequently, the sampling scheme used for the LPIII distribution follows the Bulletin 17B method of computing uncertainty for a log-normally distributed variate and applying this uncertainty to an LPIII distribution with the same mean and standard deviation as the log-normal distribution. Given this estimation of uncertainty, the samplings of the LPIII distribution (Figure C.6) proceeds as follows:

1. **Compute log-normal and LPIII distributions from sample statistics**
   The log-normal and LPIII distributions are calculated using the following frequency factor equations:

$$\log_{10} Q^s = \overline{X} + Z_p S \tag{7}$$

$$\log_{10} Q_G^S = \overline{X} + K_{G,P} S \tag{8}$$

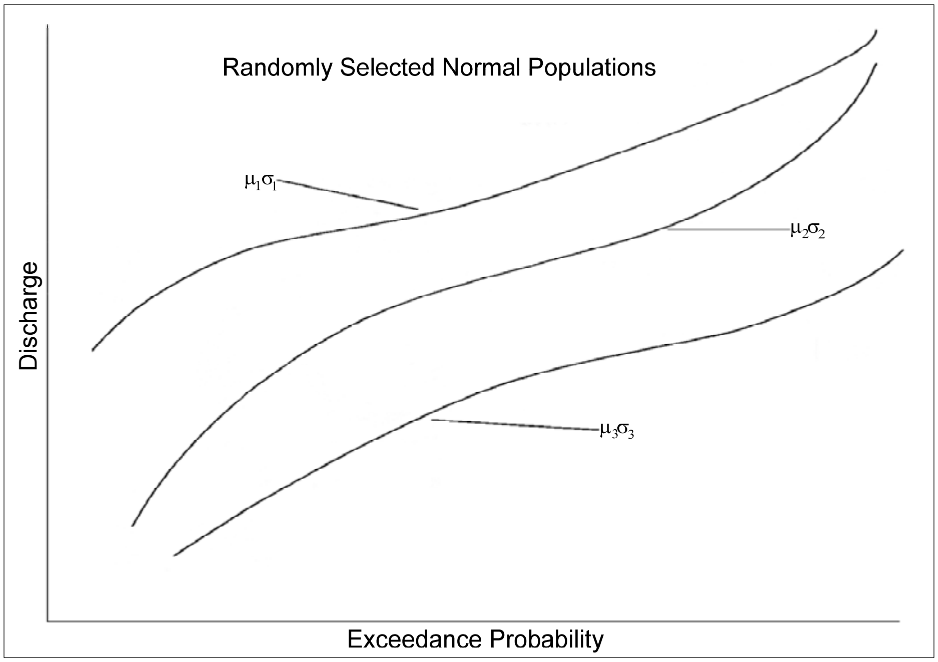


Figure C.5 Random Samples of Normal Populations from Population Parameters μ, σ

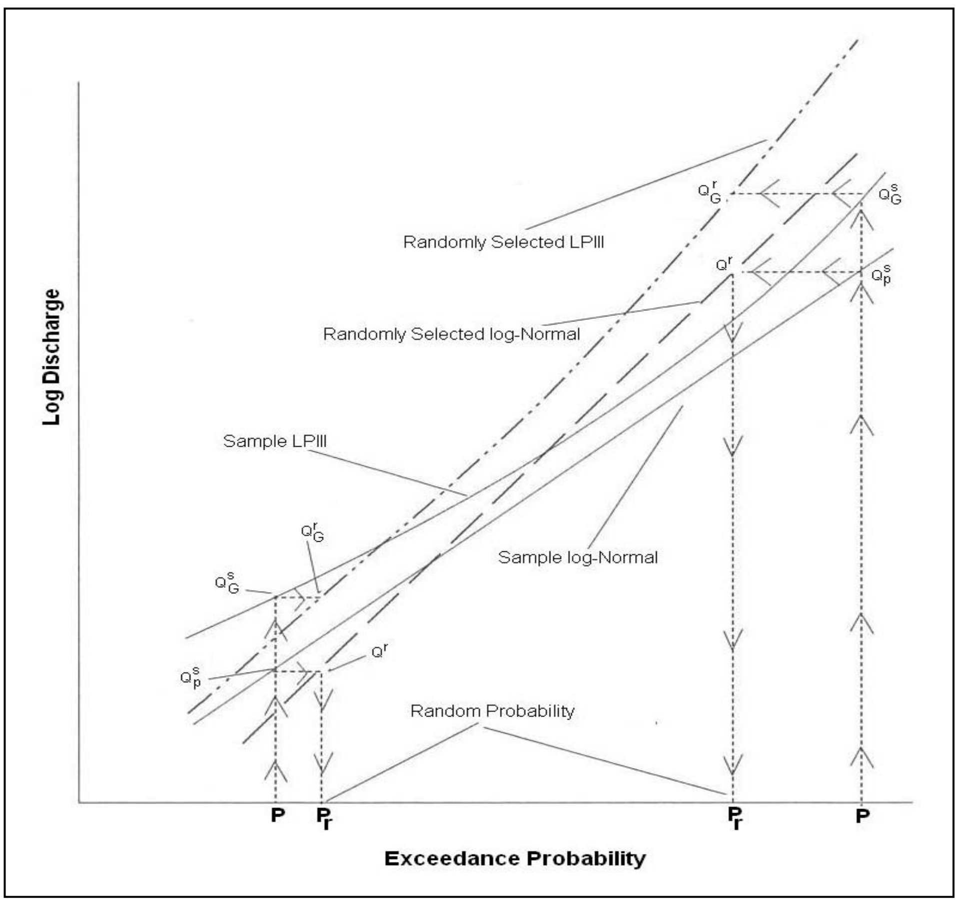


Figure C.6 Random Selection of LPIII Distribution from Random Log-Normal Distribution where Q^s and Q_G^s are respectively the flows for the log-normal and LPIII distribution, Z_p is the standard normal deviate and $K_{G,P}$ is the LPIII deviate for a sample skew G, and exceedance probability P.

2. **Randomly select a sample normal distribution**
Utilize Equations 5 and 6 to obtain a sample of the population mean and standard deviation. Compute the log-normal distribution from the population values as:

$$\log_{10} Q^r = \mu + Z_p \sigma \tag{9}$$

3. **Calculate the random probabilities resulting from the randomly selected normal distribution**
Compute the random probability associated with the randomly selected normal distribution for a discharge with exceedance probability computed from Equation 7 as:

$$P_r = \Phi^{-1}\left(\frac{\log_{10} Q_P^s - \mu}{\sigma}\right) \tag{10}$$

where $Q_P^s = Q^r$ is the flow value computed by Equation7 for exceedance probability P and Φ^{-1} is the inverse normal distribution (i.e., given a flow value, the inverse provides the exceedance probability).

4. **Utilize the random probabilities to obtain a random sample of the LPIII frequency curve**
Assign the random probability P_r to a flow value $Q_G^r = Q_G^s$, where Q_G^s was obtained from Equation 8. Compute as many pairs of P_r, Q_G^r values as needed to adequately define the sample LPIII exceedance probability curve.

C.5.3 Random Sampling of Graphical or Non-Analytic Relationships

The sampling of non-analytic or graphical relationships is necessarily ad hoc because a statistical sampling theory is not available. The algorithm used in this instance applies to any of the other contributing relationships used in the computation of EAD: 1) non-analytic stage or graphical exceedance probability curves; 2) discharge transforms; 3) rating curves; 4) wind waves and 5) stage damage relationships.

Random sampling of any of the graphical relationships is done by calculating the values for a particular confidence limit (Figure C.7). The algorithm is simply employed by: 1) generating a uniform random number between 0 and 1; and 2) calculating the confidence limit values for the particular relationship of interest. For example, if 0.95 is the value resulting from the randomly selected value, then the 95% chance confidence level confidence limit is calculated as the randomly selected relationship for the algorithm described previously. Note, that the confidence limit for a contributing relationship is randomly selected independently of other confidence limits randomly selected for other contributing relationship used in the Monte Carlo simulation.

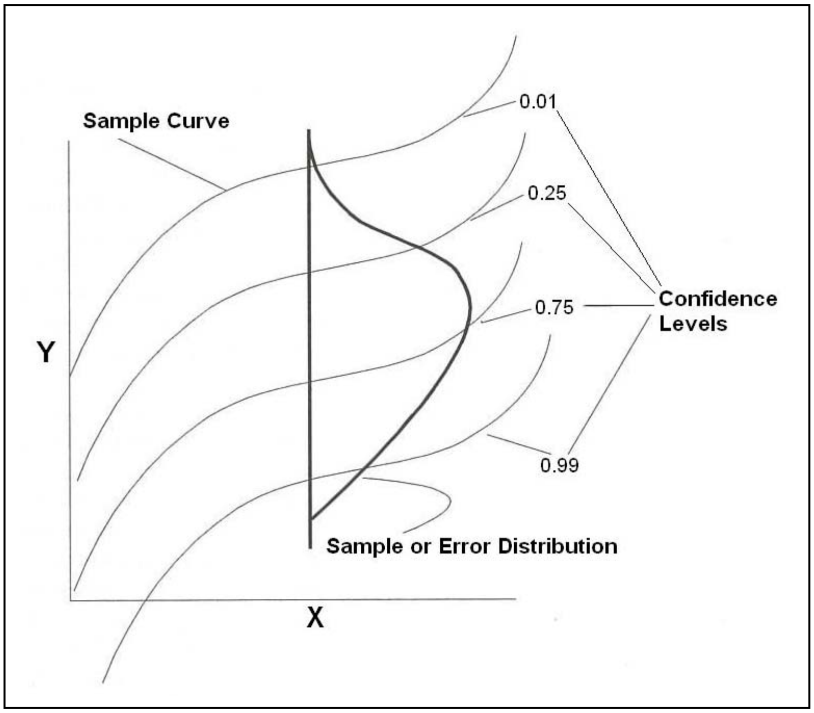


Figure C.7 Sampling of Non-Analytic or Graphical Relationships

Classical statistical theory cannot be used to justify sampling possible population values from confidence limits as is done with this algorithm. Instead, justification for this algorithm must be sought from the sampling of the log-Normal distribution described in the previous section, which relies on a Bayesian approach. As was pointed out, the Bayesian approach results in the same uncertainty distribution for population values as is obtained with a classical statistical approach to obtain the uncertainty distribution used in the 17B guidelines. In the case of the approach for graphical exceedance probability curves, the sampling from confidence limits obtained from an uncertainty distribution might be justified in analogy with this Bayesian approach.

The difficulty with this algorithm is that the sampling based on confidence limit values is very restrictive on the possible shapes of the graphical relationship. This restriction on shape results in some overestimation in the variance of the derived distribution of EAD. However, generalizing the shapes used in the sampling algorithm depends on some parametric representation of the graphical relationships. The representation is not available, leaving the current algorithm as the best available at this time.

C.5.4 Random Sampling of Uncertainty Relationships Using a Random Number Generator

The sampling of uncertainty distributions depends on the generation of uniform random numbers in the range 0.0 to 1.0 by the linear congruential method (Davis and Rabinowitz, 1967) and the transformation of the uniform numbers to the distribution desired. The linear congruential method takes the form:

$$X_{n+1} = \frac{(aX_n + b) \bmod m}{m} \tag{11}$$

where X_n is the previous number selected, X_{n+1} is the current number to be generated, a and b are constants, *m* is a constant known as the modulus, and "mod" is the modulus or remainder function. The sequence is started for n=1 by a seed value that is set to a default value within the software. The selection of the constants and seed value is critical for an effective generation's scheme. This generation scheme, as well as any other using a computer algorithm, is considered to produce pseudo-random numbers because the sequence repeats with period depending on the selection of the constants in equation (11). The constants are selected as shown in Table C.3 to obtain a long period of random numbers that is approximately equal to the size of the modulus, m. The resulting sequence of numbers has characteristics that are effective for performing numerical integration with Monte Carlo simulation.

Table C.3
Constants for Linear Congruential Method[1]

seed	1331124727
a	65539
b	0
m	2147483647

[1] Constants appropriate for 32-bit machine. Used in Equation 11.

The uniform random numbers can be used to randomly sample the graphical relationship directly. As described in the previous section, a number selected at random between 0.0 and 1.0 can be used to select the confidence level for selecting a graphical curve.

The application to the LPIII distribution requires that deviates from both a normal distribution and a chi-square distribution be obtained from a transformation of the numbers randomly sampled from a uniform distribution. The normal deviates can be obtained from the following transform due to Box and Muller (1958) (also see, Press et al., 1989):

$$n_i = u_i \left[-\frac{2\ln(s)}{s} \right] \tag{12}$$

$$n_{i+1} = u_{i+1} \left[-\frac{2\ln(s)}{s} \right] \tag{13}$$

where u_i and u_{i+1} are numbers randomly selected from a uniform distribution defined between -1.0 and 1.0, n_i and n_{i+1} are numbers that will be normally distributed, and s is computed as:

$$s = \left(u_i^2 + u_{i+1}^2\right)^{\frac{1}{2}} \qquad s \geq 1.0 \tag{14}$$

The application of this transform is accomplished by converting the uniform numbers generated over the range 0.0 to 1.0 in Equation 11 by letting $u_i = 2(X_i) - 1.0$. When the resulting uniformly distributed numbers result in s < 1.0, the current pairing is discarded and a new pair is generated. On the average, about 1.27 uniform random variates are needed to generate a single normally distributed variate.

Chi-square deviates are obtained by applying the inverse theorem (see Mood et al., 1969, theorem 12, Chapter 5). This theorem is applied by interpolating a chi-square variate from a table of the chi-square cumulative distribution function given a random probability equal to a number generated from the uniform distribution using Equation 11. The algorithm used to compute the chi-square distribution was obtained from Press et al. 1989, pg 160. The algorithm utilizes the following relationship between the chi-square and incomplete gamma function:

$$P\left[\chi^2_{N-1} < y\right] = G(a,x) = \int_0^x e^{-t} t^{a-1} dt \qquad 0 \le x \le \infty \tag{15}$$

where N is the period of record used to compute the sample standard deviation of the LPIII distribution, a = (N-1)/2, x = (y/2), and G( ) is the incomplete gamma function.

C.5.5 Numerical Error Tolerance for Simulations

The numerical integration accuracy of the Monte Carlo simulation improves with the number of simulations. The accuracy criteria developed for the simulation relies on the central limit theorem for the mean and the asymptotic normality of uncertainty distributions about exceedance probability curves. The central limit theorem (see Mood et al., 1969) states that the sample mean of any random variable is asymptotically normally distributed about the population value. In the case of this application of Monte Carlo simulation, the sample EAD results from a finite number of simulations, and the population value is the value that would be obtained from an infinite number of simulations (i.e., the no numerical error solution).

The following confidence limit results from asymptotic normality of the sample EAD:

$$P\left[-z_{1-\alpha} \le \frac{M_{EAD} - \mu_{EAD}}{\frac{S}{\sqrt{n}}} \le z_{1-\alpha}\right] = 1.0 - \alpha \tag{16}$$

where M_{EAD} is the average EAD obtained from n simulations, μ_{EAD} is the numerical error EAD, S is the standard deviation of the damage exceedance probability curve estimated after n simulations, and $z_{1-\alpha}$ is the standard normal deviate for confidence level α. This confidence limit can be rearranged to produce an error bound of the numerical integration error:

$$\frac{z_{1-\alpha} S}{M_{EAD}\sqrt{n}} = \frac{M_{EAD} - \mu_{EAD}}{M_{EAD}} \le \varepsilon \tag{17}$$

where ε is a tolerance for the confidence level α. The error bound is set in the software such that α=0.95, ε=0.01 and n$\leq$**500,000**. If the limiting number of simulations is reached the computation of EAD terminates with a warning.

A similar error bound is computed for exceedance probability function. In this case, the computed quantile (e.g., flow, stage or damage) is the mean value derived for the exceedance probability of interest. The error bound focuses on the exceedance probability where the corresponding quantile has the largest estimation standard error. This estimation standard error is set to S in Equation 17 and computed as part of the simulation. The confidence limit and tolerance are set equal to that used for the error bound of EAD. The simulations will terminate only when the error tolerance for both estimating exceedance probability function and EAD is met or when the maximum number of simulations is reached.

The error bounds constrain the numerical integration error of the simulation but does not reduce the uncertainty in estimates of EAD or exceedance probability curves. The uncertainty in estimate is a function of the error in models and estimates of parameters as indicated by the uncertainty distributions provided. The uncertainty shown by the sensitivity analysis depicted in Figure C.2 is not altered by the number of simulations performed. Rather, the number of simulations reduces the numerical error involved in combining the relationships via the algorithm depicted in Figure C.3.

C.5.6 Integrating the Damage-Exceedance Probability Function to Obtain EAD

The final computation in an individual Monte Carlo simulation is to integrate the damage-exceedance probability function to obtain a sample value of EADi as shown in Figure C.3. The damage-exceedance probability function is not analytic being derived from rating curves, stage-damage relationships, etc., that are not analytic. Consequently the following trapezoidal integration scheme is used to obtain an estimate of EAD_i:

$$EAD_i = \int_0^\infty D f_i(D) dD \sim \sum_{j=1}^{j=h} \overline{D_j}\,\overline{f_{i.j}} \Delta D_j \sim \sum_{j=2}^{j=h-1} \overline{D_j}\left(p_j - p_{j+1}\right) + D_1 p_1 + D_h p_h \qquad (18)$$

where $f_i(D)$ is the probability density function (PDF) obtained from the ith simulation, for annual damage, D; h is the number of incremental intervals of size ΔD used to approximate the differential dD; $\overline{D_j}$ and $\overline{f_{i,j}}$ are the average values of D and $f_i(D)$ over this interval, and the difference of exceedance probabilities over this interval $\left(p_j - p_{j+1}\right) = \overline{f_{ij}}\Delta D$; and, D_1p_1 and D_hp_h are end point approximations to the end intervals of integration, zero and infinity. The assumption is made in the software that $D_1 = 0$, resulting in $D_1p_1 = 0$.

The trapezoidal rule approximation accuracy improves with increasing number of intervals, h. The number of intervals is determined by computing EAD for damage exceedance probability curves determined by a sensitivity analysis such as shown in Figure B.2 prior to performing the Monte Carlo simulation. The sensitivity analysis is performed by obtaining damage exceedance probability curves by combining confidence limit estimates of the contributing relationships at the same confidence level. The confidence limits investigated are obtained for confidence levels, 0.5, 0.75, 0.25, 0.9, 0.1, 0.99, 0.01, 0.999, 0.001.

The number of intervals, h, is obtained by performing recursive integration for each confidence limit investigated in the sensitivity analysis. The recursive procedure involves: 1) selecting an interval size; 2) computing EAD; 3) dividing the interval size in half, where appropriate, and re-computing EAD; 4) computing the relative difference between EAD values obtained in steps (2) and (3); and 5) determining if the relative difference in step (4) is less than 1%; if this tolerance is met; then the interval used in step (2) is selected; otherwise steps, 2-4 are repeated with the interval size used in step (3) used in step (2). The division of interval sizes in step (3) is only performed when the interval size reduction will make a significant difference to the computation of EAD. This limits the number of intervals used which is important to the computational efficiency of Monte Carlo simulation. The more intervals used, the more computational time required to perform a simulation. Intervals are divided until the error tolerance is met or the maximum number of 200 is obtained. Experience has shown that 200 intervals provide sufficient accuracy given the data typically available.

C.6 Uncertainty Distributions

C.6.1 General

The estimation of uncertainty distributions for the contributing relationships will involve a certain amount of judgment, except for the case of a flow or stage exceedance probability curve where the uncertainty is determined from the length of record. The judgment used in estimating uncertainty for other contributing variables should correspond to the same factors contributing to uncertainty in the exceedance probability curves. The uncertainty in the exceedance probability functions is due to the estimation uncertainty in the parameters, which are the mean and standard deviation for the LPIII (the skew being ignored).

This focus on parameter uncertainty effectively examines the uncertainty in the mean relationship given a set of scattered observations. In other words, the focus is on the uncertainty in fitting an exceedance probability function to an observed set of plotting positions and does not reflect the scatter of the plotting positions about the best estimates.

To understand the difference between uncertainty in fitted relationships and the uncertainty due to scatter, consider a split sample exceedance probability analysis of a gage having 100 years of record. Estimate both pairs of frequency curves and determine the top ranked event from separate 50-year records. In general, the difference between the 1% chance flow estimated by the frequency curves will be considerably less than the difference between the top ranked events. The smaller variation in the fitted relationships, as compared to the plotting positions, represents the difference between uncertainty for best fit relationships and that for scatter about these relationships. If uncertainty in the contributing relationships such as rating and stage-damage curves is based on scatter, then the specified uncertainty will be too great. This in turn will probably increase the magnitude of the EAD best estimate and certainly increase the variance of the EAD distribution.

Therefore, the principle focus of estimating uncertainty should be on the potential variation in the best estimate of the contributing relationship. Consequently, if a sensitivity analysis is performed to determine the uncertainty in a contributing relationship, such as in varying Manning n to determine errors in rating curves, then the parameters varied should be reasonably likely to occur together. Combining extreme parameter values probably reflects scatter rather than the reasonable variation in a fitted relationship.

The error distribution about exceedance probability curves is determined by the effective record length and the type of exceedance probability curve specified. In the case of the LPIII distribution, the uncertainty is computed as described previously. Also, refer to ETL 1110-2-537 for the method used to calculate the uncertainty distribution for non-analytic (graphical exceedance probability curves). Normal, log-normal and triangular error distributions are available for specifying uncertainty about other contributing relationships, as is described in the next two sections.

C.6.2 Triangular Error Distribution

The triangular distribution is the simplest available for use with contributing relationships that are not exceedance probability functions (Figure C.8). This triangular distribution is specified for either: 1) each paired value describing the contributing relationship (e.g., discharge- stage function); or, 2) for a specified value in the paired relationship (e.g., for 1,000 cfs corresponding to a stage of 10.0 feet). In the case of the specified value, the bounds on the error distribution are linearly interpolated to zero for values less than this specified value and remains unchanged for values greater than this value.

The parameters of the distribution are the mode and the range. The mode is the most frequently occurring value, or the peak of the probability density function for the triangular distribution. The range is simply defined by the minimum and maximum possible values for the dependent variable in the paired relationship.

Inspection of Figure C.8 shows that the triangular distribution need not be symmetric. The effect of the asymmetry is to cause the mean or expected value associated with the triangular distribution to be different than that for the mode. Consequently, Monte Carlo simulation will produce on the average a contribution relationship that is different than might be assumed to occur when specifying the mode as a no uncertainty estimate of the relationship.

C.6.3 Normal and Log-Normal Distributions

The normal distribution is specified by a mean and standard deviation of the errors (Figure C.9). The log-normal distribution also is specified by a mean and standard deviation of the logarithms (base 10) of interest. Consequently, estimation of the errors needs to be performed in log space

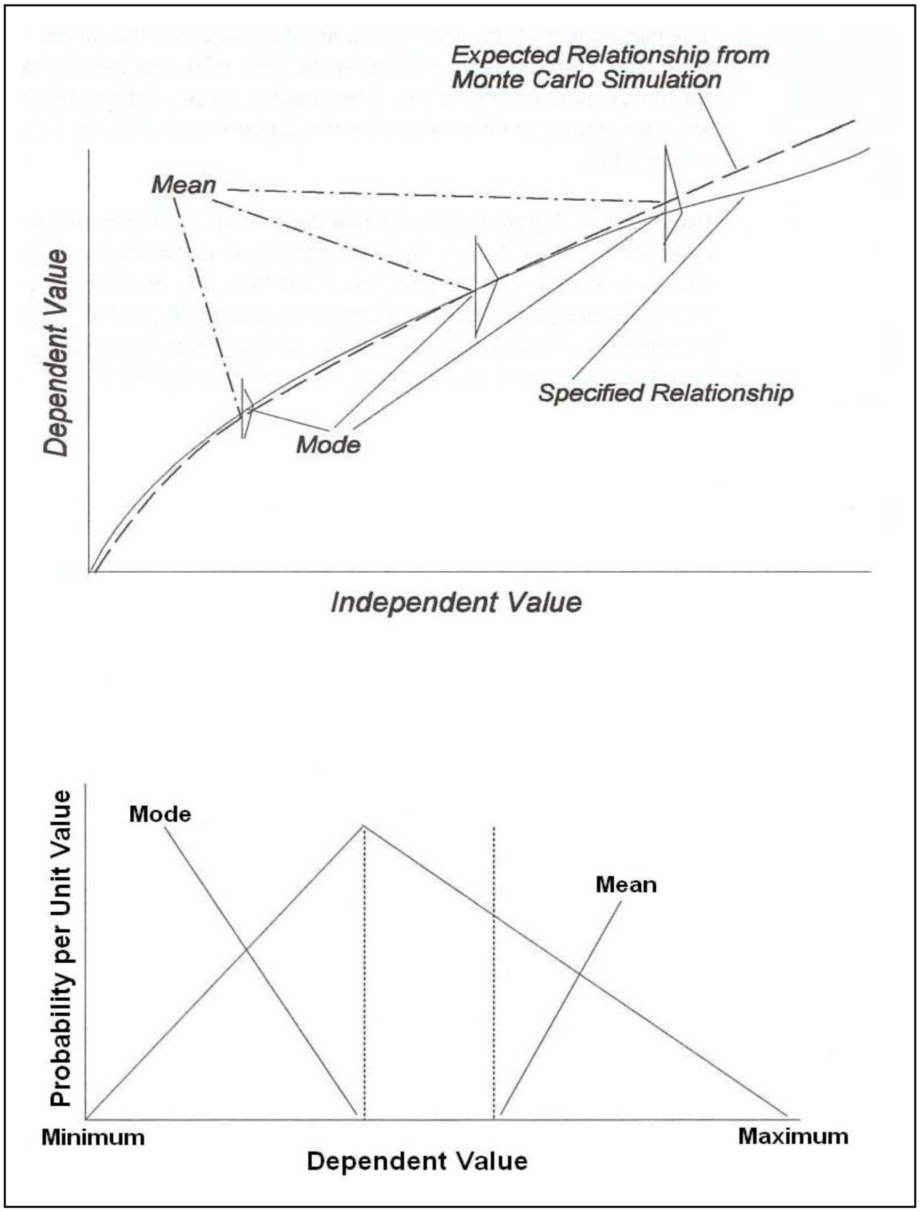


Figure C.8 Triangular Distribution Application

for this distribution. For example, the paired values of discharge and stage should be plotted on $\log_{10}$-$\log_{10}$ scale; and the best fit relationship and the errors should be determined from this scale. The relationship is then specified by the untransformed best fit values (i.e. by taking anti-logs of the best fit) together with the standard errors of the logarithms.

The normal distribution is symmetric with respect to the mean. Consequently, the mean or expected relationship obtained from the Monte Carlo simulation will be the same as the specified relationship. This differs from the average result obtained with an asymmetric triangular uncertainty distribution as explained in the previous section and shown in Figure C.9. The estimation of the log-normal distribution is most conveniently performed in log-space, thus reducing the problem in estimating a normally distributed log variate. However, the log-normal uncertainty distribution is asymmetric when plotted on a linear scale, and, like an asymmetric

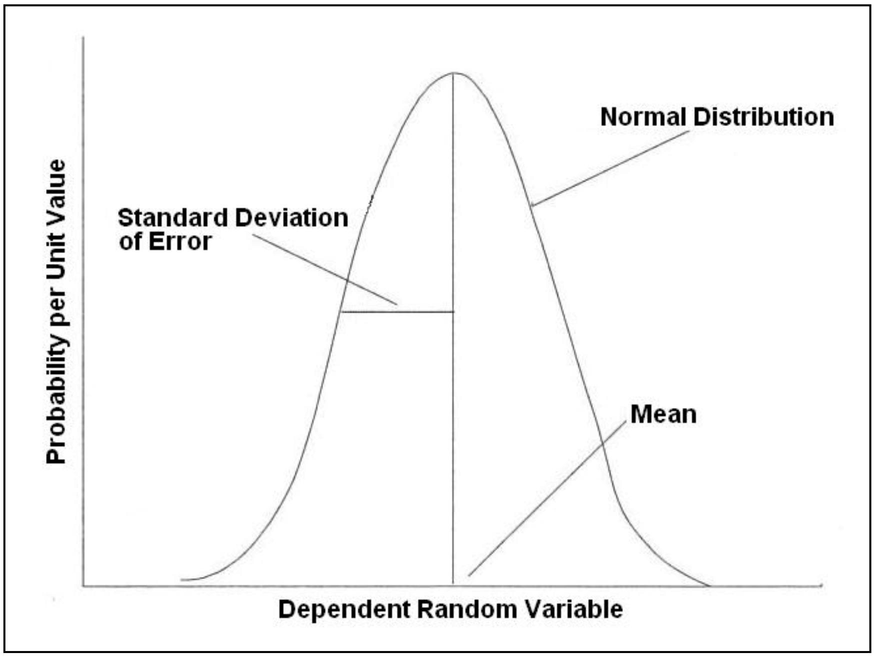


Figure C.9 Normal Distribution of Errors

triangular distribution, will result in an average relationship that differs from the specified relationship when performing a Monte Carlo simulation.

C.6.4 Application to Stage versus Damage Relationships

The Monte Carlo simulation algorithm reduces the computational effort required by only computing total damage. However, stage versus damage is specified for each damage category with a corresponding uncertainty in the estimates. The total damage is easily obtained by aggregating the specified (no uncertainty) estimates in the case of triangular and normally distributed uncertainty distributions. Logarithms of the specified estimates are added in the case of log-normally distributed uncertainty distributions.

The uncertainty distributions are not so easily aggregated. The assumption is made that the uncertainty estimates are uncorrelated. Consequently, the standard errors of the normal distribution and the log standard errors for the log-normal distribution can be added by summing these standard errors squared and taking the square root (variances added). The triangular distribution is handled in the same manner in that the maximum and minimum ranges are added to obtain the range of an equivalent triangular distribution.

C.7 Levee Analysis

Computation of damage exceedance probability functions with levees is straight forward when the levee only fails due to overtopping, but requires some additional computations when geotechnical failure can occur. The computation of the damage exceedance probability curve for levee failure due to overtopping only is easily done by setting the zero damage point to a stage corresponding to the top of levee. The integration of the damage exceedance probability curved using equation (18) to obtain EAD is then applied as without a levee.

The computation of the damage exceedance probability curve when geotechnical failure is possible needs to consider the probability of failure below the top of levee. The damage exceedance probability curve is calculated in this situation as follows (Figure C.10):

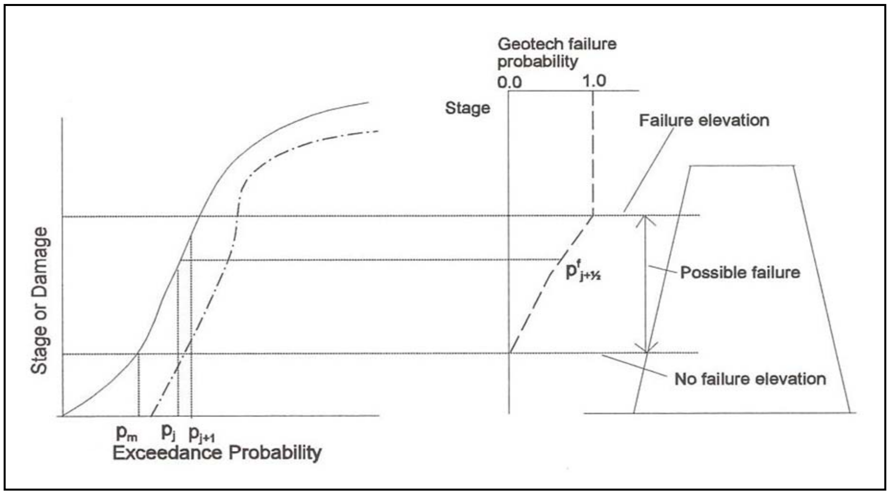


Figure C.10 Damage Considering Levee Geotechnical Failure

$$P\left[d_j \le D < d_{j+1}\right] = \left(p_j - p_{j+1}\right)p^f_{j+\frac{1}{2}} \qquad p_j \le p_m \tag{19}$$

where P[d_j-≤ D < d_{j+1}] is read as "the probability that the annual damage, D, will be in the interval $d_{j-1\le}$ to d_j"; p_m is the exceedance probability corresponding to the stage that cannot cause damage due to geotechnical or overtopping failure; p_j and p_{j+1} are the exceedance probabilities for stages that cause damage corresponding to $d_{j\le}$ and d_{j+1} in the absence of the levee; and $p^f_{j+1/2}$ is the failure probability of the levee for the stage with exceedance probability midway between p_j and p_{j+1}. Equation 18 then can be applied to this damage exceedance probability curve to obtain EAD by letting:

$$\overline{D_j} = \frac{d_j + d_{j+1}}{2} \tag{20}$$

and substituting:

$$\left(p_j - p_{j+1}\right)p^f_{j+1/2} \rightarrow \left(p_j - p_{j+1}\right) \tag{21}$$

C.8 Project Reliability and Flood Risk Computations

Reliability is computed as the exceedance probability for a target stage or the likelihood of levee failure. Flood risk is defined as the probability of one or more exceedances of the target stage or levee failures in a specified number of years.

The target stage is determined by interpolation from the stage versus damage relationship using a specified fraction of a damage for a specified exceedance probability. This damage is determined from a damage-exceedance probability function obtained by combining traditional estimates of the contributing relationships (i.e., contributing relationships without uncertainty) for the without-project condition.

The exceedance probability for this stage or the levee failure probability is specified as both a "median" and “expected” value. The median value is obtained from the stage-exceedance probability curve obtained by the traditional (no uncertainty) method. The expected value is obtained by averaging the target stage or levee failure probability over all the Monte Carlo simulations.

The risk of flooding one or more times in NR years is computed as:

$$R = 1 - (1 - p)^{N_R} \tag{22}$$

where p is either the probability of exceeding the target stage or levee failure. An expected value of R is reported as the average over all Monte Carlo simulations.

C.9 References

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